ROBOTICS

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BEFORE THE

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ROBOTICS

WEDNESDAY, JUNE 2, 1982

House of Representatives,
Committee on Science and Technology,
Subcommittee on Investigations and Oversight,
Washington, D.C.

The subcommittee met, pursuant to call, at 9:45 a.m., in room 2325, Rayburn House Office Building, Hon. Albert Gore, Jr. (chairman of the subcommittee) presiding.

Mr. Gore. The subcommittee will come to order. It is a pleasure to welcome our witnesses and our guests today to the first indepth congressional hearing on robotics. Robot technology is growing rapidly and provides the United States with an excellent opportunity to improve our Nation's productivity and enhance our position in world markets. In fact, robotics will be in the forefront of the next industrial revolution which will be based on the use of intelligent machines in industrial processes. The United States spent $130 million on robots in 1981, and by 1990 the experts believe the United States will be spending $2 billion on robots or 40 percent of the expected worldwide expenditure of $5 billion.

A robotic system can be defined as "one capable of receiving communication, understanding its environment by the use of models, formulating plans, executing plans, and monitoring its operation." Most industrial robots today, including those with computers, have little or no sensory capabilities. In fact, these robots can function only in an environment where the objects to be manipulated are precisely located. But future robots will make significant contributions not only to manufacturing, but also to space activities, underwater exploration, medical surveillance, microsurgery, and many other areas.

In 1981, of the approximate 4,000 robots installed in the United States, almost one-third of these robots belonged to only six firms, and more than half of the robots were being used in the auto industry. Experts have forecast anywhere from 20,000 to 100,000 robots will be installed in the United States by the year 1990, and approximately 1 million by the turn of the century. Real gains in productivity, although presently difficult to quantify, will occur with the development of large robotic-based systems and eventually an automated factory.

Together with the issue of robotic technology, we as a nation must also plan for those who may be displaced as a result of this new technology. Other congressional committees will in the future be examining this important topic. My colleague from California, George Miller, will have a hearing next week, I believe.

The purpose of this hearing is twofold. First, the subcommittee will be assessing the current state of the art of robot technology, both internationally and in the United States. Secondly, we will be examining current areas of research and determining what research should be emphasized in the mid and long-term to improve our Nation's competitiveness in the world's market.

This hearing appears to be timely. Japan, as well as the other major economic powers, has taken aggressive steps to insure a strong robotics capability. The United States is currently behind Japan and the Soviet Union in the production of robots. In 1980, the United States only produced 1,269 industrial robots whereas Japan produced 4,493, and the Soviet Union produced between 2,000 and 3,000. The Ministry of Trade and Industry of Japan has embarked on two major projects. The first was an ambitious project started in 1977 to build an automated factory, or flexible manufacturing system (FMS) as it is also called.

Japan has made great technological strides in this area. MITI has recently announced a 7-year, 30 billion yen—approximately $150 million—national robot research program to develop Japanese robot technology so it does not have to rely on United States or European technology. Japan clearly recognizes the role of robotics to improve its productivity and insure preeminence in world markets.

Similarly, the Soviet Union has established a national plan for robotics development. Even though the Soviet Union is behind the United States generally in some robotics technology, it has made excellent progress in some important theoretical research areas.

To date, the United States has not articulated a national plan, but I am pleased to note the increasing amount of robotics research by companies, nonprofit labs, and major universities in the United States. Additional research will be needed to improve accuracy, dynamic performance, sensors, control systems, mobility and software programs. With the increased emphasis on research and the closer university/industry cooperation, these tough challenges can be met in a timely fashion to insure our competitiveness with other nations in the world marketplace.

Major issues to be examined today are:

One. The implications of robots on industrial and economic growth.

Two. How does the United States' robotic effort compare with other major industrialized countries?

Three. How will industry respond to advances in robotic technology?

Four. What research areas are being emphasized by industry and universities?

Five. Do we have sufficient scientifically trained manpower to meet the challenges of robot technology? and

Six. What role should the Government play?

Later this month we will have a second day of hearings when selected Government witnesses will be asked to testify about Federal initiatives to promote robot technology.

Today we will be hearing from three panels of experts. The first panel will be discussing the development of robotics in major countries other than the United States. The second panel will be discussing the current state of the art in the U.S. industry and what future research is needed to insure U.S. competitiveness. The third panel will be discussing the current university research and areas of research that need to be emphasized in the mid to long term.

In addition, we have a special expert panel from the National Science Foundation who will, at the conclusion of each panel's oral testimony, assist the members of the subcommittee with its inquiry to insure a comprehensive record on this important topic.

Our first panel of witnesses is made up of Mr. Paul H. Aron, Daiwa Securities America, Inc., and Mr. Joji Arai, manager of the U.S. Liaison Office of the Japan Productivity Center out in Arlington, Va.

Mr. Aron, we would like to begin with you. Without objection the entire text of your prepared statement will be put into the record and we would like to invite you to proceed in any manner that you see fit.

STATEMENTS OF PAUL H. ARON, DAIWA SECURITIES AMERICA, INC., BAYSIDE, N.Y.; AND JOJI ARAI, MANAGER, U.S. LIAISON OFFICE, JAPAN PRODUCTIVITY CENTER, ARLINGTON, VA.

Mr. ARON. Thank you, Mr. Chairman.

Mr. GORE. Before you do so let me just introduce our expert discussants who are going to have questions to assist the subcommittee in making a complete record on this difficult and new subject.

Dr. Jack Sanderson, who is Assistant Director of the Directorate of Engineering at the National Science Foundation. Welcome.

Dr. Bernard Chern, Program Director of Computer Engineering with the Division of Electrical, Computer and Systems Engineering at NSF.

And Dr. Alvin Strauss, with the Mechanical Engineering Department at NSF. We are delighted to have all three of you here and we welcome your participation.

Mr. Aron, welcome. Please proceed.

Mr. ARON. The United States has clearly been the pioneer in the area of industrial robots. In fact, it enjoyed at least a 15-year lead in research and an 8-year lead in production compared to Japan and compared to the Soviet Union.

The 1981 survey of robots in operation, conducted by the Robot Institute of America, a trade association, indicated, as of yesterday anyway, 4,700 operating robots in the United States. The Japanese reported 67,435, but that is using a Japanese definition, which includes as robots many machines which we do not include as robots. Using the American definition the figure would be 14,246 robots in operation.

The Soviet Union, the latest figures we have, somewhere between 6,000 and 7,000 by U.S. definition. This is a Soviet figure, not mine.

As far as production for the year 1981, the production of industrial robots in the United States was probably something in the neighborhood of 3,000. Production in Japan was somewhere between 8,000 and 9,000, and production in the Soviet Union is probably somewhere between 3,000 and 4,000. The 1985 figures for the number of robots in operation, as estimated by each country now, are as follows: in the United States the estimate for 1985 would be

15,000 robots, U.S. definition; for Japan, at least 85,000 by the most conservative estimate, but probably closer to 100,000; and in the Soviet Union somewhere between 40,000 and 42,500.

The question is what happened to that lead that the United States had enjoyed both in research and production? I don't think that we have lost the lead in terms of research. I don't know of any robot in the world with the sophistication of, say, a Cincinnati Millacron, T-3. We certainly have the most sophisticated robots in the world, probably the most advanced robots in the world.

But in terms of robots in operation, Japan in particular, about which we know a great deal, has certainly far more. Why did this occur? The basic success for the Japanese in robots lie primarily in three factors.

One, the employment practice. This is probably the major factor. In the large scale Japanese manufacturing firms, employees have lifetime employment to the age now of approximately 60. That means they have employment security, not job security, and do not fear loss of a job as a result of introduction of robots or any other form of automation.

In addition, all employees of the company receive a bonus twice a year, once in June and once in December. That bonus is determined largely by how well the company has done. In the case of Toyota, last year the bonus was 5½ months pay for the year for each employee. A third element of this is the company is responsible for the retraining of workers displaced by change in production methods or change in markets.

The employee thus has no fear of loss of employment. He sees automation as an improvement of both quality and productivity and therefore a larger bonus. He also sees that the company retraining program means that he moves from a physically tough job, manually hard, environmentally unhealthy, hot, repetitive, dull, and he moves from that into a much higher job like learning how to be a software engineer. So for the Japanese employee the battle cry is bring on the robots because for many it means greater pay, greater bonus and a greater chance to move up the ladder.

What has been the major difference has been that labor in Japan has not merely passively accepted robots, it has actively helped in the application of robots. This has been done largely through various production circles involving both management and labor, with different names like quality control circles, zero-defect circles, and so on. One example I just might give for a minute, the Tochigi plant of Nissan. It has a welding shop of 248 employees. In the period of 19 months in the period from February 1979 until September 1981, productivity in the 19-month period rose 22.1 percent. Just in that shop alone. It is a shop which uses, by the way, 50 robot welders.

Now the man who headed this effort found out that when there were production problems, a worker was aware of 100 percent of the production problems, the foreman was aware of only 79 percent but the management was aware of only 4 percent of the production problems a worker faced on the line. The result is that what Japanese have done has been to incorporate the employees so that they can get and learn to apply robots more effectively and more efficiently.

What we have basically in Japan is that the worker not only contributes his hands, he also contributes his head. They do not have that sharp differentiation between the head of the plant and the hands. Or the bosses and the horses. Rather, they have employee participation in problem solving. This has been a major factor.

I would indicate, for example, that this little Nissan plant, they are now averaging 38.7 suggestions per employee per year for the improvement of production, 38.7 suggestions. They have a minimum quota of one per month. I don't know how much of this is ritual and how much is real, but certainly it has played a factor.

A second factor in superior robot application has been management. Management in Japan has a long-term view. They have lifetime employment as an employee. They do not have the option method, which is available to Americans; they are deprived of that opportunity. Therefore, they don't have to be concerned about the price of the stock. The price of the stock in America is what determines the value of the option. If you have a bad quarter, the price of the stock goes down, options become less worthwhile. Therefore, the management in America, because of its options, tends to avoid introduction of equipment and machinery which would cause a downturn in earnings, however temporary it might be.

Another factor is that the Japanese do not permit takeovers. In order to arrange a takeover in Japan the board of directors of the company taken over has to vote to approve the takeover. Since the board of directors in Japan consists of senior management, with very, very few exceptions, the only time there has been a takeover has been when the company faces imminent bankruptcy. Short of bankruptcy it is just not possible to have a takeover.

This means that without the ability to take over other companies, or buy them, the Japanese have to develop their own technology. The inability to get experienced people means you have to develop your own people. This has been a major factor in the Japanese success.

Another very important element is the low interest rate. In the United States we have a prime rate running 16 percent; in Japan, 6 to 7 percent. Therefore, payout is a much different thing for the Japanese than it is for the Americans. In line with this, the Japanese manager is burdened with the necessity of maintaining full employment. In Japan the cost of labor is a fixed cost, not a variable cost, he can't fire them, he has to constantly look for new markets, new methods, new techniques. The result is that the source of innovation in Japan comes from the large company looking for new techniques such as robots to improve production and develop new products.

With very few exceptions most robots developed in Japan have been developed within the company rather than by special robot companies. Because they are developed within the companies, the companies very often have anywhere from 3 to 5 years experience before the robot comes to market. Therefore, a Japanese robot that comes to market is generally completely debugged. Not only is it completely debugged, it is also part of a system because they have used that robot system within their own plant to produce. They know what a robot can do. They have organized a total system. So the Japanese robot that comes into the market is a robot that is capable of operating at once and as part of a system.

Because there are large companies involved and because they have used robots continuously in production, they can assign huge staff to the robot development. For example, one company alone, Hitachi, with 8,000 people in R&D, has assigned 500 people to robot. R&D, the largest number of people assigned to robots in America as far as I know is Unimation with an assignment of 90 people to robot R&D.

Another company, like Matsushita, has just announced they are having an exhibit, starting tomorrow, of ten new robots which they have been using over the last several years. They already have within their plant 5,000 such robots operating now. Now they are just coming to market offering them in the Japanese market, yet they have already put into operation 5,000 within their own operation.

A second element is a difference in management, then. The Japanese specialize in robots for particular industries. The Americans have tended to develop a universal robot that can do everything.

The third element besides labor and management is the role of government. The government has played a very positive role in the development of robots in Japan. For one thing, the government encouraged the development of the Japan Leasing Corporation which leases robots. This corporation is owned 70 percent by robot manufacturers and 30 percent by casualty insurance companies. It borrows money at low cost and leases robots to people. The term of the lease is 6 years for a full payout lease, but they are also available, 2- to 3-year leases. So the companies that want to use robots don't have to worry about making a huge plant and equipment expenditure. They can get the robots at a much lower price through leasing.

A second element has been that the government has supported low interest loans to small and medium corporations to incorporate robots.

A third element is the government provides an extra 13 percent depreciation for installing a robot. With a double declining, say, 5-year life term, it means the first year you can deduct 40 percent for normal depreciation plus another 13 percent for extra depreciation, or you deduct 53 percent of the cost of the robot in the first year of operation. That 13 percent has to be given back in five equal payments beginning in the sixth year after introduction of the robot providing you introduce other machinery you pay much later.

The Government has been a very important factor in subsidizing the Japan Industrial Robot Association, which itself engages in many research activities. For example, it provides interest-free loans to members to develop marketing, to develop application techniques. The Japan Industrial Robot Association develops an enormous amount of research so that not only do the Japanese know what is going on in Japan, what applications they have learned from Japan, but they translate every bit of material, including all the patent applications filed wherever they may be, all detailed and in Japanese.

Where they can't keep up with it, they have followed what a company like Nippon Electric has done, that is simply been to teach their engineers English. We, for example, in America have very little translation of materials on Japanese robots. We are not taking advantage at all of their experience and knowledge. We may very well be reinventing the wheel, not knowing it is already in operation in Japan.

In like manner, at least publicly, we are not translating the vast amount of material available on Soviet robots. And there are major books available on Soviet robots, complete details of layout, operation, electronic capability, what they do, how they do it. Of course it is in books. But I think it would be useful to have this material and be able to make some judgments.

Another element is the R&D program in general. One thing we have to understand. The Government, by and large, has permitted R&D to be largely done by the private companies. There is R&D by the colleges and by public institutions. These are supported to some extent. The Government contributions often are very low because they do not include in the support for R&D such things as payment for teachers and payment for people in research. They only include in the allocation for R&D a payment for machinery, equipment, so forth. So the data on Japanese Government supported R&D is probably underestimated.

Nonetheless, basically what you have is a development of R&D supported substantially by the Government, but done largely through private enterprise. I would just like to present in "1 minute" sort of a fast view of what is going on in all the rest of the world, which in 1 minute may give you some perspective.

The production of robots in Western Europe has been, by and large, relatively limited. In the case of Germany, where we would have expected a large amount of robots to be developed, there are about 1,400. The reason lies largely in the fact that German production is much more dedicated to capital goods, which are primarily custom built. A robot will operate best in a medium-size production, what we call batch production. Therefore, this individualized custom production is not so applicable to Germany.

Where the Germans have applied robots is obviously in the area of automobiles. Volkswagen is the biggest manufacturer of robots. But, by and large, the manufacturers' use of robots in Germany today is somewhere in the area of 1,400.

In France, largely dedicated to things like fashion, luxury goods, and handmade goods, there is not that driving need, though there is a development of electronics and industry growing in France. However, the French lack a machine tool industry, which is a weakness by and large. They do develop very fine sophisticated robots largely by Renault, which is a major automobile manufacturer.

In Italy, we have brilliant ideas but not capital, and also labor hostility. In Norway and Sweden we have brilliant ideas. Here the markets of both Norway and Sweden are far too limited.

In the case of the United Kingdom, they have had a very difficult time of being able to transfer what they know in the university into the workplace. Probably the element of unemployment is a major factor. It seems to me, in looking at the whole picture, what has happened is that the strength of Japan lies primarily in application. We have concentrated far too much on developing technology without recognizing that a great deal of what could be done is what you learn from the actual application of robots.

We have developed far too sophisticated machines, which are fine and necessary, but we have not done enough in the development of less sophisticated machines. This whole argument about definition of robots places undue stress on the fact that the Japanese do not have as good robots as we. But the point is whether the robot is more or less sophisticated; the robot doesn't know it. When the production line pours out, it is recognized in the marketplace. The Japanese have made a much wider application of their robots, however unsophisticated.

I think we must be concerned not only with technology but also with a very important element largely ignored in America, the role of manufacturing engineering, production engineering, and application of robots. This is an area I think that provides a huge gap in the American approach.

[The prepared statement of Mr. Aron follows:]

STATEMENT OF PAUL H. ARON, EXECUTIVE VICE PRESIDENT, DAIWA SECURITIES AMERICA, INC.

The United States, the pioneer in industrial robots, enjoyed a lead over Japan in industrial robots of at least fifteen years in research and eight years in production. Japan imported its first industrial robot in 1967 and Kawasaki Heavy Industries, after concluding a technology license agreement with Unimation in November 1968, produced in 1969 the first robot in Japan.

Nevertheless, the RIA's worldwide survey of installed operating robots includes a Japanese report of 67,435 robots versus a U.S. figure of 4,700. The Japanese lead is by no means so overwhelming. Their report includes manual manipulators and fixed sequence machines which the Americans do not define as robots and do not include in their data. Limiting the Japanese robot population to the American definition indicates a figure of 14,246. (see appendices 1 and 2)

In the Fiscal Year 1980, ending March 31, 1981, Japan produced by Japanese definition 19,873 "robots" with a value of ¥78,426 million (roughly $356 million using a convenience exchange rate of ¥220 = $1.00), and by U.S. definition 4,493 robots with a value of ¥49,262 million (roughly $224 million). U.S. production for 1980 was reported as 1,269 units with a value of $100.5 million. For 1981 U.S. production is estimated at about $150 million while Japan, based on output for the first six months, might be estimated at 8,500-9,000 units with a value of $400 - $450 million. In my recent trip to Japan last October, I heard some bullish observers forecasting 1,000,000 installed robots in Japan by the year 2000 or earlier. Nevertheless, I believe that the present Japanese lead in robot production and installation is not so overwhelming as many observers believe. It is only the end of the first quarter of the football match, and while Japan is leading 14 to 4, three more quarters still have to be played. We know from history that the future is never simply a continuation of the past and that human activity alters and changes the best of projections and computer printouts.

To change the present directions of events, people must be able to analyze and understand them. It is for this reason that an analysis - an objective analysis - of the past, present, and the future of Japanese robotics is useful. Objective analysis rejects the blind adulation and slavish imitation that has of late become so popular. Objective analysis does not disregard the Japanese failures and the long time-frames often required for success. At the same time, objective analysis rejects the dismissal of Japanese successes as the result of some unique cultural tradition that is incomprehensible to others or at least unachievable by them.

Japan's success in robot production and installation can be traced in very large measure to its labor practices. The Japanese employees have not merely passively accepted, but actively implemented robotic applications. Japanese employees in major corporations enjoy lifetime employment until retirement age, formerly set at 55 but now nearing 60. Upon "retirement" the employee receives in a lump sum, one month of salary for each year of service (usually 3 or 4 years pay at the exit wage) and may continue to work for the company or a subsidiary, but no longer with a guarantee against a layoff.

All employees receive two bonuses annually, each ranging from 2-5 months pay, in June and December which, while negotiated between the union and management, are ultimately based upon company profitability. The Japanese unions with very few exceptions, are not organized by skills, crafts or occupations: the union is on a company-wide basis and covers all members of the bargaining unit, often including employees of component makers. Employees identify with the company not with a skill and they can and are often shifted from one job to another within the company. The employee enjoys employment security not job security.

Not fearing loss of employment, the employees do not oppose technological innovation; in addition, as automated production generally enhances quality and profit and consequently the bonus, the Japanese employees welcome and seek for the success of the robots.

In Japan the company assumes the responsibility for retraining the employees who have been displaced whether by changes in markets or in production methods. Lifetime employment deprives most companies of the opportunity to recruit skilled workers from other companies and therefore requires training of its own employees to cope with new production methods and new products. Not fearing the loss of their trained workers, companies are encouraged to devote considerable effort to this training. As robots are used largely in dangerous, unhealthy and repetitive jobs, the employees consider production by robots as a means of relieving monotonous and environmentally harmful, might I add inhuman, tasks in manufacturing. Employees displaced by robots have moved to jobs, more challenging intellectually and less demanding physically.

Some have argued that these practices such as lifetime employment are limited to about 1/3 of the labor force, but it is the third which is employed primarily by the large manufacturing companies which have been the focus of robotic application. Some see the Japanese unions as particularly docile. But it is important to recognize that the unions maintain simultaneously both adversary and non-adversary relations with the company. Both seek to increase the size of the pie. They work together to improve productivity and quality. But in collective bargaining management and unions are adversaries, especially every Spring when the unions undertake the labor offensive to increase wages. Strikes are rare and of short duration. Who among the managers or employees would wish to endanger the bonus by a long strike? The employees and the union often through union-management joint consultation committees, are kept fully informed and know long in advance of the plans and problems of management.

This policy combining employment security and sharing in the benefits of productivity made possible the growth of small groups among the employees who studied and suggested methods to improve output, both qualitatively and quantitatively. Japanese management views the employees as fully committed to the company, both their hands and their brains. The Japanese company does not differentiate between the "head" and the "hired hands". All the employees are called upon to solve the company's problems and ideas emanate from both the top and the bottom.

The practice of small production study groups, variously called Quality Control circles, Zero-Defect circles, J-K, etc, have played a vital role in developing employee participation in problem solving. These voluntary teams of 8-15 employees, begun only in 1962, started at first to study only quality problems and to suggest improvements. During the 70's these teams expanded in number, they involve possibly as many as 10 million people now, and increased the range of their activities from quality to many other areas including productivity and conservation of raw material and energy. Studies indicate that both the unions and particularly the QC circles have often been involved in working out robot applications within the plants. It should come as no surprise that those companies with the most active QC circles have also been the leaders in robotization.

One of the largest Japanese companies in 1981 summarized the results as follows: "If it had not been for the voluntary efforts of workers to acquire mastery over new technology and equipment, such know-how would not have taken root no matter how much money had been spent in buying foreign equipment and technology."

Of course, the relatively high tempo of real economic growth, with its consequent demand for increased labor, has more than compensated for the losses of jobs resulting from increasing productivity, automation, and robotic applications. The initial introduction of robots in Japan in the early 70's was not very successful largely because of the wide divergence of labor and robot costs. Before the 1973 "oil shock" Japanese labor costs were still relatively inexpensive while industrial robots were still high-priced and not very efficient because of the low level of electronic development. In 1970 the annual labor cost averaged ¥990,000 while a playback robot cost ¥12,000,000, a ratio of 12.1 to 1. Today the average annual wage in large-scale manufacturing (including bonuses) is about ¥4,000,000 while playback robots are available at less than ¥10,000,000 a ratio of 2.5 to 1. Superficially a playback robot can be amortized within three years on a single shift if it replaces just one worker and within one year if it works around the clock. The actual expenses of robot installation, production modifications and maintenance result in a slower rate of amortization. In the future labor costs are expected to grow 6-7% annually, while robot costs, thanks to declining microprocessor costs and economy of scale in production, should remain level or decline. Given an aging and increasingly educated labor force, the Japanese see the robot as the means to perform the arduous and dreary tasks that the labor force may be less able physically and less willing intellectually to perform.

The Japanese seem to believe that they displaced the U.S. as the "Number One" in robot production largely because of the labor problem. In America and Western Europe, the introduction of robots is frequently debated and the crucial point in such debates is the unemployment problem. In this era of high unemployment American unions are willing to accept automation and robotics, but only if job security can be maintained. This is rarely discussed in Japan and instead the positive effects of robots are discussed: improvement of quality and productivity and greater safety for the employees. Stress is placed on the new opportunities for greater and higher level employment, as robot operators, robot maintenance workers, and "software engineers", and for opportunities in new industries such as ocean resource gathering made possible by robots. Unlike Japan, few U.S. companies have assumed the responsibility for retraining workers that could be displaced by robots. Furthermore, the American worker does not directly benefit from the increased savings and profit created by robotics.

A case study may be useful to illustrate the methods and consequences of employee participation problem solving. The Nissan Tochigi Plant has a body welding department of 248 workers and 50 robots that made the Datsun 310. In a period of nineteen months (Feb. 1979 - Sept. 1980) productivity was raised 22% with virtually no capital expenditures and no additional employees. The leader of the effort was S. Yoshida who headed the department.

Nine years previously, Yoshida had studied a factory in Japan, investigating 197 production problems. He theorized that assembly line workers would see more of the problems than managers who were "removed from constant direct contact with the assembly process". His study indicated that the workers identified all of the 197 production problems, the foreman 79% and the manager only 4%. In this study and his later activity at the Tochigi plant, Yoshida involved the workers in "identifying the problems and finding solutions". He found that "people have latent abilities to be innovative, creative and extremely competent in problem solving when they are given an opportunity to use their talents and receive recognition for their efforts".

In the trim and chassis operation of Japan's automative assembly plants, workers are "encouraged" to take turns performing the different jobs. This familiarity with the entire process facilitates the workers' voluntary efforts to rearrange plant layout or to change the operator's job assignment simultaneously to improve productivity and to reduce the operator's burden and fatugue. Eash worker is responsible not only for the quality of his output but also for those of his assembly line co-workers. Yoshida considers job rotation to be "a very important part" of the process to assure quality.

Yoshida's studies of production data of the Tochigi welding operation indicated that maximum hourly output averaged 98.7% of the designed systems capability but at some times output reached 131.1% of that capacity. A target of 111% average was to be accomplished in 8 months. In fact, the goal was achieved in 5 months by eliminating chronic breakdowns through worker-oriented problem solving efforts. During this period the Mean Time Between Failures (MTBF) "jumped up 2 times longer". Robots had been plagued with the "Monday Disease" - frequent system failures on

Monday morning after the robots had been repaired and modified during the weekend. Workers were trained to enable them to make some repairs on the line to the system. Workers were asked to record any line stoppage exceeding one minute and any symptoms such as noise or vibration associated with the trouble. Production engineers analyzed these records daily and suggested corrective maintenance action. Yoshida noted that work stoppages could be the result of some petty detail such as the position of the welding gun or the position of a sheet metal piece.

Yoshida's shop challenged other Nissan body plants to increase productivity. This began Phase 2 - that lasted from August 1979 to January 1980 - the target was 4% reduction in Machine Cycle Time (MCT) and equalization of MCT for each station. Tochigi developed an effective emergency manual back-up system in the event of robot failure. The workers learned through their quality control circles the appropriate welding guns to be used for particular spot welding operations. Workers also learned how to perform minor maintenance such as repositioning the robot welding arm or replacing cooling hoses.

Phase 3: began in February 1980 with the target of 122.2% of designed production capacity. The "Monday Disease" was significantly eliminated by simulated testing of the entire system during the weekend. Workers, on their request, to economize and save time, ground the welding tips formerly done by outside maintenance people. Eight committees consisting of workers and supervisors were formed: Safety, Traffic Accident Prevention, Quality Control Circle Administration, Awards, Job Enlargement, Suggestion Encouragement, and Quality Assurance. Each member of the Safety Committee patrolled the area of his KUMI (a basic work unit of 20 workers and a foreman) pointing out unsafe conditions to his co-workers. Each member of the committee reported daily to the chairman before work started. The Traffic Committee provided lectures on driving safety. The Suggestion Committee decided to encourage all workers to present new ideas, at least one each month. The number of suggestions made by workers for improving productivity rose annually from 2.7 in 1977, to 7.6 in 1978, to 18.32 in 1979, and finally to 38.7 in 1980. (11,624 suggestions from 248 employees including administrative employees). By teaching workers to inspect their own work, the Quality Assurance Committee in one year gradually replaced inspectors. Workers and foremen organized task forces to solve problems with the assistance of production engineering and maintenance workers. One task force, Total Production Maintenance (TPM) encouraged workers to minimize systems breakdowns by their own efforts such as "cleaning, checking, minor replacement, and prompt feedback of system trouble information to the maintenance workers". Yoshida concludes that "At first the workers' efforts look trivial, but they will become a mountain of improvement."

In the past year a series of studies have been undertaken by the Government, both MITI and the Ministry of Labor to determine the import of robots on employment. Union leaders and union members have voiced some misgivings - they do not oppose robotization but are concerned about potential unemployment. In a recent meeting that I had with a MITI official involved in the robot area, he expressed the view that at present robots did not threaten employment but he was not sure of the effecte in 1985 and 1990. MITI could be faulted for not having undertaken studies and prepared measures now if the unexpected were to occur in 1985. The interim report on the electric industry prepared by the All Japan Federation of Electric Machine Workers Union and the preliminary survey of the Ministry of Labor's two year study on microelectronics indicate that the level of employment has been maintained although workers have had to change jobs and relocate. The shortage of skilled workers in manufacturing industry especially in small and medium firms is acute - the labor force in secondary industry is growing at only .7% annually. The aging of the labor force is another concern because older workers are considered more difficult to retrain. The better-educated young worker is considered more easily trainable for the new knowledge intensive jobs. The number of information processors is expected to increase in Japan from 130,000 in 1980 to 796,000 in 1985. The Japanese recognize that they must focus increasingly on training methods and production systems that can make use of the older workers.

Japanese management on all levels has been more responsive to the introduction of robots than their American counterparts and were largely responsible for pushing robotic application during the unrewarding period of the early 70's. Life time employment has created greater security and a more long-range attitude among Japanese managers. The absence of stock options reinforces this long term attitude for the profitable exercise of stock options depends upon stock prices which at least in the U.S. are largely dependent upon the course of bottom line earnings per share.

Because of the long term relationship, Japanese management has been willing to take a longer view. Japanese managers are able to tolerate the high initial costs of incorporating robots into production and are willing to accept a much longer payoff than their American counterparts. In the first year of robot introduction, costs can be very high--not only increases in depreciation, interest costs, and miscellaneous costs related to the robot (changes in the plant and its equipment to accomodate the robots), but also interference and slowdowns in the production while the robot is being fully integrated into production. In one case study in Japan, for example, the company had anticipated that robots would increase production and thus would permit write-off of all costs within the first year. Instead, production declined and total costs grew by 30%. Similar experiences have caused many American managers to abandon their robot programs. But the Japanese persisted and at the end of the second year, total costs were 25% less than if the product had continued to be produced manually.

Japanese managers are generalists, often shifted from one area to another that may bear little relationship to their previous experience. On the other hand, American managers tend to be specialists and stay within one area of work during their entire career. This, at times, creates opposition, if not hostility, to an innovation such as a robot that might undermine their position. American reports are replete with tales of opposition to robots by middle and lower managers and conflicts between manufacturing engineers seeking to introduce new technology and production departments seeking to maximize current production and intolerant of any interference in output. Even the front line of American management, the foreman, often see the robot as a threat to their status especially when the robot requires "care and feeding" by an inexperienced youth with a training in electronics who substitutes knowledge for strength.

Japanese managers do not have the opportunity of corporate takeovers. A merger is possible only with the approval of the Board of Directors of the company to be taken over. Since the Board in Japan consists almost entirely of active senior management, only the threat of imminent bankruptcy, with very few exceptions, has compelled the acceptance of a takeover.

In the absence of a takeover strategy and driven by the need to maintain employment (in Japan wages are basically a fixed not variable expense) Japanese managers must constantly seek new opportunities for employing their assets (both human and non-human) by internal expansion.

In 1979-82 while Japanese managers of necessity concentrated on new product development and new production methods, a large segment of America's corporate leadership dedicated its energies to a "merger and acquisition mania". From the beginning of the first quarter of 1979 to the end of the first quarter of 1982, American corporations spent $170 billion on acquisitions. It was deemed less expensive to acquire someone else's profitable assets than to tke the risk of building up one's assets. American management has become increasingly financially oriented, running the company like a portfolio of stocks, often with a short-term orientation. Using the discounted cash flow method with high assumptions for rates of return leads to two results: either the new projects are rejected because they cannot meet the financial goals or the promoters of the project exaggerate the possible returns. Thus American robot makers have often declared that robots can provide a full payback in as little as one year. When adopted, the robots do not measure up to the promised goals. The evident result is unemployment of robots which does exist in the U.S.

In an atmosphere of relatively high interest rates, the financial side of U.S. management constantly seeks shorter and shorter payouts and American roboticists often see these "bean counters" as their enemy. The non-adversary relationship and the long-term outlook which pervades the Japanese company has successfully coped with the issues of robot introduction.

American and European companies were also, to some extent, side-tracked in robotics as they often concentrated on the most expensive robots. At the same time, the Japanese developed robotics gradually from the unsophisticated manual manipulators to more complex systems that incorporate "intelligence".

Americans stress innovation and sophistication and many companies complain that they cannot retain engineers if they are assigned only to state of the art applications. The dream of the American engineer is to establish an independent small company to make an important breakthrough. After the breakthrough the engineer expects his company to be acquired by a large conglomerate. The engineer anticipates receiving an ample financial reward and then, if he is young, to proceed to create another high-technology company and repeat the process. Thus the engineer devoted to production often has less prestige and does not attract "the best and the brightest" of the students.

The Japanese engineer largely expects to remain with the large company. The Quality Control circles that seek to improve application in the Japanese companies are supervised by the Japanese Union of Scientists and Engineers. Production engineering in Japanese companies often enjoyed equal or greater prestige than innovations. This seems to be changing now as the Japanese are beginning to realize the necessity of creativity.

At present over 150 firms in Japan are manufacturing robots of whom 55 are members of the JIRA. Most large manufacturers, actual or potential, are JIRA members but some important exceptions should be noted: Nitto Seiko, Sailor Pen, Pilot Pen, Yamaha, Nippon Denso, TDK, Takeda.

The existing robot makers are widely distributed over the whole range of business scales. In size of capitalization, robot makers are broadly distributed from small firms to giant corporations. In examining the table below, the 55 small companies with less than ¥100 million capitalization (equal to about $455,000) represents 41.4% of the enterprises; the medium firms with (¥100-300 million) represent 23.3%, while the firms with over ¥3 billion capitalization (equal to about $13,636,000) represent 35.3% of the corporations. The same trend is evident when we examine the robot makers by number of employees. The small firms with less than 500 employees represent 46.6% of the total, the medium firms with 500 to 5,000, 30.1%, and the giant firms with over 5,000 employees, 23.3%. This data, based on a JIRA survey in 1979, of 133 robot makers, is shown below:

Industrial Robot Maker Distribution
By Size of Capital

Less than ¥10 million	19 companies	14.3%
¥10 million - ¥100 million	36 companies	27.1%
¥100 million - ¥1 billion	23 companies	17.3%
¥1 billion - ¥3 billion	8 companies	6.0%
More than ¥3 billion	47 companies	35.3
Total	133 companies	100.0%

Industrial Robot Maker Distribution
By Number of Employees

Less than 50	33 companies	24.8%
50 - 500	29 companies	21.8%
500 - 1000	15 companies	11.3%
1000 - 5000	25 companies	18.8%
More than 5000	31 companies	23.3%
Total	133 companies	100.0%

This is confusing because sometimes a large company may establish a wholely-owned subsidiary usually quite small devoted largely to robot manufacturing. For most companies robots constitute less than 5% of total sales.

It also should be noted that only a few but important companies in Japan are using licenses from non-Japanese robot makers. Kawasaki Heavy Industries, a major factor in the spot welding market, has a license from Unimation, while Kobe Steel produces painting robots under license with Trallfa. However, most Japanese companies are making robots of their own design, although the similarities with leading American and European models can be quite striking.

Most Japanese firms developed robots initially for their own needs and many firms such as Yamaha, Nippon Denso, Honda did not offer them publicly. Hitachi, Matsushita, NEC and Toshiba developed robots for various welding and assembly applications within their own companies. Okamura originally used its robots for welding and transferring in the manufacture of steel furniture. Sailor Pen originated a robot for injection molding of its components which was later used on a large scale in the production of plastic boxes for audio tapes. Shin Meiwa developed a robot for arc welding its dump trucks. Komatsu originally used its robots for welding shovels of its construction equipment; from this it ultimately developed a very simplified robot language PLAW (Programmed Language for Arc Welding). Pentel's robot was originally used to assemble parts of its mechanical pencil.

Some robots were developed by electronic and/or engineering companies to be used by sister firms. Mitsubishi Heavy Industries and Mitsubishi Electric developed robots originally used by Mitsubishi Motors. Toyoda Machine Works developed and is developing robots for Toyota. That Mitsubishi Electric should develop a "Window Washing Robot", promoted as guaranteeing privacy in hotels and high office buildings can only be understood when we know its sister

Mitsubishi Estate, owns many of the tall buildings in Tokyo's Wall Street.

Many companies developed robots to protect or extend their product line. Fujitsu Fanuc, the major manufacturer of NC equipment, developed loading and unloading robots for machine tools that work in conjunction with NC machines. In the process of making these robots, Fanuc saw the need for assembling robots and finding none satisfactory for its purpose developed its own. Fanuc's robots do not yet make robots, but Fanuc does have a production line labelled "experimental" where servo-motors, an essential ingredient of a robot, are largely but not entirely assembled by assembly robots. To market its assembly robots, Nippon Electric Corporation in turn developed NC machines. The machine tool makers such as Ikegai and Okuma, to protect themselves vis-a-vis Fanuc in turn developed loading and unloading robots for machine tools. Aida, a manufacturer of hydraulic presses developed press-feeding robots and Komatsu followed suit. Both Matsushita and Osaka Transformer, manufacturers of arc welding equipment are offering arc welding robots. Nitto Seiko, a manufacturer of mini screws, is now making an assembly robot with a screw driving capability.

The market for robots in Japan is largely splintered and competitive,unlike the U.S. where two robot makers hold over one-half of the market share, The Japanese market is widely dispersed and changing each year. In the U.S., despite the many new companies entering the field, companies actually manufacturing robots probably number about 20 compared to about 150 in Japan. Kawasaki Heavy Industries has only 3-5% of unit volume and 6% of total value of all Japanese robots (by Japanese definition). Yaskawa, the second largest robot maker accounted for 4% of production value in 1980. Most companies own only 1-2 % of the robot market.

The two largest pure robot manufacturers, Motoda Electronics and Dainichi Kiko each had sales of about ¥1,200 million (about $5.5million) in 1980.

In many respects the production of robots in Japan resembles the fierce competition that grew up among manufacturers of television sets, digital watches, desk and hand calculators and video-tape recorders. After a period of intense competition among many firms, production ultimately was concentrated in a few large firms. It should be noted that this period of competition also resulted in Japanese domination in the world market for these products. As the spokesman for the Long Term Credit Bank of Japan confidently puts it: "It is only a matter of time before the industrial robot becomes one more piece of merchandise which symbolizes Japan".

The Japanese are currently debating the future of this structure of robot makers. Some expect no radical change in the industry structure within the foreseeable future. They believe that the small to medium enterprises will continue to carve out markets for themselves in the many specialized areas. Others visualizing the increasing role of minicomputers and intelligent robots expect that the large electric manufacturing companies because of their superiority in IC and LSI technology, will dominate the robot industry. At present, each individual robot maker has its own area of special expertise such as Yaskawa in arc welding, Kobe Steel in large paint sprayers. Aida in press application, Fujitsu Fanuc in machine tool processing. However, all makers are using the technology developed in their specialty area for applications of other areas. Kawasaki is the most active in this approach with its Unimates entering almost all areas of application. But many other manufacturers are aspiring to be "universal robot makers". The emergence of an electronically-oriented universal robot maker depends on the rate of development of intelligent assembly robots.

This industrial structure has given the Japanese several advantages. The American robot manufacturers must sell their robots to users; few can test their equipment in actual production conditions at their own plants. With the entry of IBM, Texas Instruments, GE and Westinghouse into the robot market, this should be altered. But in Japan all through the decade of the 70's the major manufacturers now emerging, Hitachi, Matsushita, Toshiba, had been using robots within their/own companies. No adversary relationship nor gap existed between supplier and consumer because they were one and the same.

Because the robots were used within their own factories, the robot makers in Japan offered for sale not just robots, but total systems which already had been tested for several years in their own factories. This compelled companies that had originally just produced robots to begin to develop total systems.

The Japanese robot makers have developed a huge experience in robotic application and in system organization incorporating robots and other equipment. Because of their organization they had on call huge resources. Fujitsu Fanuc has only 800 employees, but its parent Fujitsu, Japan's largest computer maker, provides electronic support. Fuji Electric, a close associate, produces inspection robots and offers complete factory systems incorporating the products of its own manufacture and of its close associates. Two other close associates are important: Fuji Heavy Industries, a major heavy engineering manufacturer and producer of the Subaru, an important market for robots, and Furukawa Electric, producer of fibre optics, now reportedly being tested in robots to reduce weight and increase efficiency.

The big electronic manufacturers can direct huge resources into robotics. Hitachi has 16,000 employees in R&D including 8,000 highly trained engineers and technicians of whom about 550 hold doctorates in science of engineering. Its 1980 R&D budget was ¥128 billion ($582 million), about 3.8% of sales. Hitachi has assigned 500 of its staff to its in-house robotics project - to roboticize over half of Hitachi's assembly operations by 1985. Matsushita is reported to have planned the production and installation in-house of 100,000 robots by 1990 with teams assigned to develop robot systems for positioning, assembling and testing of its products. Additional robots are to be produced for sales outside of Matsushita. Thus the large Japanese electronic-electrical manufacturers have a sufficient market inside the consolidated company to provide an economy of scale.

Matsushita is holding an exhibition in Tokyo (June 4-6) dedicated to Factory Automation. Matsushita already has 5,000 robots operating inside the company. It is displaying a complete line of 10 new cartesian-type assembly models (4 new types). Marketing in Japan is to begin this month and export is planned to start with a year. Prior to this announcement Matsushita had been selling only Pana-Robo robots (two models) primarily for arc welding.

It is quite evident that MITI has been interested in robots since the beginning of the seventies. It would seem unlikely that JIRA would have been formed without some government encouragement. However, it was not until 1978 that the industrial robot was officially designated as an "experimental research promotion product" and as a 'rationalization promotion product" with promulgation of the special Machine Information Industry Promotion Extraordinary Measures Act. While the Electric Machinery Law in 1971 had defined an industrial robot, industrial robot terminology was first standardized in 1979 under the Japanese Industrial Standards.

Following the typical policy of cooperative rather than adversary relations with business, the Ministry of Trade and Industry (MITI), having identified robot production as a major strategic industry for Japan's future, undertook several measures to popularize their utilization.

With MITI encouragement, if not direction, a robot leasing company, Japan Robot Lease, (Jarol), was founded in April, 1980 with the initial paid-in capital of ¥100 million. This company is jointly owned -- 70% by 24 JIRA members and 30% by ten casualty insurance companies. The aim of JAROL is to support robot installation by small and medium-scale manufacturers and increase their productivity. As 60% of operating funds are financed by low-cost loans from the government's Japan Development Bank, and the rest from the Long-Term Credit Bank, Industrial Bank of Japan and the city banks, JAROL is in a position to lease industrial robots under conditions more advantageous than the ordinary leasing companies. For its first year of operation (fiscal year 1980), JAROL planned ¥700 million robot leases; actually its leasing contracts numbering 52 amounted to ¥1,150 million (about $5.7½ million). The average term of the lease was 6.5 years and provided a full payout. In April, 1981 JAROL offered a more flexible 2-3 year rental agreement (not a full payout) and after the expiration of the agreement planned to rent the robot to the same or a different user. At the same time JAROL began discussions with MITI to enter overseas leasing of robots. This resulted from a request of an Australian firm to lease Japanese-made robots. Some questions arose as to the propriety of using government loans for overseas leasing but JAROL suggested loans from the Japan Export and Import Bank. Positive action on this matter will greatly strengthen Japan's competitiveness in overseas industrial robot markets.

Miti has arranged for direct government low-interest loans to small and medium-scale manufacturers to encourage robot installation for automating processes dangerous to human labor and for increasing productivity. The government budgeted for fiscal year 1980 ¥5.8 billion for these loans which are extended through the Small Business Finance Corporation, a government finance agency.

MITI has permitted the manufacturer who installs a robot to depreciate 13% of its initial purchase price in the first year in addition to taking ordinary depreciation. This extra depreciation is a common practice in Japan when MITI seeks to promote a particular industry or product. Extra depreciation has been as high as 50%. Generally, it can be taken over a three-year period and is usually repaid in five annual installments beginning in the sixth year. By installing an industrial robot, a firm can depreciate 53% in the first year, 13% plus 40% (5 year depreciation double declining).

It seems quite evident that MITI subsidizes to varying extents JIRA projects. It is often difficult to see where MITI ends and JIRA begins.

JIRA provides interest-free loans to its full members which are to be used for test marketing, using its total funds of ¥710 million ($32 million).

JIRA sponsored various studies , all 100% government subsidized, in 1981 - Computer Assisted Robot-system Engineering (¥15 million); System Design for Mining and Life-Saving (¥10 million) and Releasing Workers from hazardous working conditions (¥20 million). Other studies, each costing ¥5 million, received a government subsidy of 75% - automating the buffing process, automating the coating process, automating assembly, welding and painting of large storage tanks. The JIRA English language study of robot specifications and applications in Japan cost ¥8 million of which ¥6 million was subsidized. The 11th International Symposium on Industrial Robots held October 1981 in Tokyo cost ¥15.3 million of which ¥11.5 million were covered by subsidies.

JIRA has been active in translating and summarizing robot data including patents, research articles, etc. from all over the world into Japanese. (Few translations from the Japanese are publicly available in English and Americans are deprived of a vast storehouse of experience on robot applications. The U.S. government does not make publicly available translations of Soviet materials on robots. At least three major Soviet works - one on the structure of industrial robots which includes considerable data, diagrams and pictures of various Soviet and foreign models; one on computerized robots including algorithmic systems and robot languages; and one on robot experimental research and diagnostics.)

JIRA and MITI provide excellent statistical data. JIRA research into robot markets receives considerable MITI assistance. One such recent publication lists 233 non-manufacturing applications of robots - to be described later.

MITI created an atmosphere favorable to the introduction of the industrial robot, but it had depended largely on the private companies to determine the direction and scale of production and to undertake R & D.

Research on robotics in Japan is conducted by three major types of institutions--colleges and universities, national and public research institutes, and research laboratories of private firms. The number of robot research laboratories in universities and public research institutions grew from 43 in 1974 to 85 in 1980. In fiscal 1979, the universities spent 100 million yen (or about $.5 million) on robot research and the public research institutes about 220 million yen (about $ 1 million). This total of about $ 1½ million is hardly a very large amount. But this statistic omits "personnel expenditures" and is therefore a substantial understatement. Some 270 researchers at colleges and universities and 80 researchers at institutes worked on robots in 1979. Public research has concentrated on theoretical problems, many of which have direct and immediate application such as--speed control (acceleration of robot when its gripper holds nothing), improved positioning accuracy, simplification and modularization of robots, sensory perception, pattern recognition ability.

The expenditure of private enterprises on robots has not been made public but up to now has been the overwhelming source of robotic R & D. Of the 107 robot manufacturers surveyed by JIRA in 1979, twenty had a specialized robot research division in their in-house research laboratories, while another fifty-two without a special robot research division had one or more researchers specializing in robot research.

The private research laboratories have concentrated on R & D most closely linked to application--increased speed, miniaturization, computer control, weight reduction and modularization (development of interchangeable robots).

A major change recently occurred--MITI announced a seven year ¥ 30 billion national robot research program to begin April 1, 1982. MITI will create a new R & D group to carry out the program whose purpose is to make robots suitable for a wider application and to develop Japanese robot technology instead of relying on imported American and West European know-how. Stress is to be placed on intelligent robots especially for assembly work, and on robots for nuclear, space, oceanic, and earth-moving industries. The development of sensory perception, language systems, and motional capacity are to receive top priority. This program is called a nationally important major technology development scheme.

Future Trends in Japanese Robotics

1. Assembly Robots

Japan will place major stress on robotization of the assembly process - inserting, screwdriving, nut tightening, bonding, sealing and similar processes. The electrical/ electronic industry is taking the lead in this endeavor. The application of Flexible Manufacturing Systems to the machinery industry is accelerating in Japan. But what is not being given sufficient attention in the United States is the extension of the FMS to assembly. This involves a total system - automated warehouses, automated conveyor systems, loading/unloading, palletizing and transfer robots, unmanned vehicles, assembly robots, inspection robots, computer assisted manufacturing. The industrial robot is merely the top of the iceberg.

The Japanese have at least 50 FMS or unmanned plants. The term "unmanned" is not fully accurate. The Fanuc plant in Fuji has a total staff of 100 including management and clerical workers, but the plants' machines with the assistance of robots and pallet chargers can and do work through the night with possibly only one man watching the operation on a screen. Of course, each machine is set to cease operations in case the supplies are used up or in the event of a malfunction.

The Yamazaki FMS plant has two shifts of 6 people each and a third shift of only one person, a watchman. Fanuc has been incorrectly described as a plant where robots produce robots. The robots help to make parts for the robots but the robot is still assembled manually. However, Fanuc is running an experimental assembly line where servo motors are largely assembled by Fanuc's own assembly robots.

In 1981, the major electronic/electrical manufacturers such as Matsushita, Hitachi, Toshiba, and NEC publicly announced plans to robotize about 50% of their assembly production processes and in the same year, a plethora of new assembly robots appeared in Japan.

The Japanese have developed their own assembly robot - the SCARA (selective compliance arm for robot assembly.) This jointed arm has considerable speed - up to 1,000 mm/s. It was developed by Professor Makino of Yamanashi University who was supported by a consortium of Japanese manufacturers. Several of the consortium are now working on SCARA robots - Nitto Seiko, Pentel, Sankyo Seiki, Hirata. One model of the NEC assembly robot is quite similiar to SCARA. Yamaha has made a SCARA type robot which it is using to help assemble motorcycle motors. Fanuc, Hitachi and Matsushita have developed fast moving assembly robots. While Professor Makino considers the PUMA superior to SCARA, the latter reportedly sells at about half the price and in the opinion of Professor Makino is eminently suitable for most assembly purposes. (IBM has adopted Sankyo's Scara robot).

The FMS has required improved inspection robots to keep pace with the increased speed of assembly. Japan's excellent camera industry can be a major contribution to visual sensory perception. Japanese companies are applying the latest developments in optical fibers to tactile perception. Assembly and inspection robots will be the fastest growing segment of Japan's robot industry. Arc welding likewise is expected to grow very rapidly while spot welding and painting robots should continue to grow but at a decelerating rate.

To increase Japan's competitiveness, especially against its low labor cost competitors in East Asia (South Korea, Taiwan, Singapore, Hong Kong, Malaysia) robotics is being planned for industries such as clothing and shipbuilding where labor inputs are high. The Japanese see the flexible manufacturing system as a means to cope with increasingly diversified demand that requires medium batch and multi-product production.

The industrial robot is viewed as a major vehicle to reduce all inputs not just the labor input. The industrial robot is viewed as a means to reduce capital expenditure. Product design modification and model changeover can be achieved not by radically rebuilding special purpose machinery but by changing the robot's program, set-up time can be reduced and costly retooling of the production line eliminated. By operating on three shifts, the robot can reduce investment.

The industrial robot can also reduce raw material consumption by reducing the ratio of defective workpieces and can reduce energy consumption by working in unpleasant environments requiring less lighting, ventilation and air-conditioning.

2. Modularization

Instead of a highly sophisticated and therefore expensive robot that can be employed in a very wide variety if functions, the Japanese are stressing modules - each capable of a limited number of activities which can be combined to produce the desired results. Thus, in spot welding, one control panel may control simultaneously up to 8 units (48 axes) while a hydraulic unit separate from the robot's main body can control three robots. These modules provide the same flexibility that "mix and match" offered to women in their choice of clothing.

The Japanese refer to this as the BBS - Building Block System and several companies have adopted this approach. A study of two years of operation of BBS welding in an auto plant indicated 30% greater efficiency than the conventional robot system. The floor space required was reduced in half while the downtime of a BBS robot was one third that of a conventional robot. Matsushita plans to utilize the modular approach in its in-house robotization efforts and expects to develop three different types - robots that position work pieces accurately, robots that assemble work pieces, and robots that adjust finished products to function as originally designed. The BBS provides greater flexibility to manufacturing and is a useful but not necessary component of the Flexible Manufacturing System.

3. Application of Existing Technologies

The Japanese have been willing to accept, test and produce with existing machinery rather than wait until complete refinement and absolute perfection are achieved. Their employee participation makes it possible to improve and modify the robots while they are being used. Since the robot manufacturers generally also manufacture other products, they have available to them in-house testing and much wider experimentation in actual operation.

In addition, the Japanese have not proceeded to produce increasingly sophisticated robots searching ever for more esoteric innovations. Fanuc first developed its Model M2 which can service as many as five machine tools. This evidently did not prove to be practical and it is being phased out. Instead, Fanuc produced M1 and M3 somewhat less complicated and able to handle fewer machine tools. Later, Fanuc developed its M-0 and now its M-00 which are even simpler, less sophisticated and at the lower end of the robot spectrum. The Japanese have not feared to move backwards to less complex machines while their competitors seem driven to produce increasingly complex robots capable of a wider range of actions but also considerably more expensive.

By not being as rigid as its competitors in the definition of robots, JIRA has included members who produce manual manipulators and fixed sequence machines. But by being part of the industry and also sharing in the government and non-government encouragements these producers of the simple machines have often upgraded their equipment into the playback class. The vagueness of the Japanese language has been a positive help.

4. Growth of Non-Industrial Applications

In like manner, JIRA has involved itself in the use of robots in non-industrial areas and has provided detailed market analyses of demand for 233 different non-industrial applications: agriculture, forestry, ocean development, construction, mining, nuclear, medical and services. The analysis included the number of years required for acceptance, the number of robots required for the first 5 and 10 years of the application, the maximum number of robots for the particular use, and the average price that can be expected for the type of robot. The development of non-industrial robots will greatly assist the growth of industrial robots. Though they may differ in use and structure, many of the components and technologies are quite similiar. This will bolster the economy of scale for industrial robots and contribute to the improvement of robotic technology.

5. Spread of Robots to the Small Manufacturers

Although initially robot application seemed to be concentrated mainly in the large scale manufacturing companies robots are expanding into the small companies. Favorable governmental depreciation, special financing for small companies and robot leasing have made the robot accessible to a wider variety of firms. The small firm in Japan is especially impacted by the shortage of skilled labor and the aging of the work force. In like manner, the application of robotics in the large plants necessitated robotic applications among the small firms that supply larger firms. The extension of robotics to small plants and even one-man operations also enhances the economy of scale.

6. Growing Popularization of Robots

The Japanese have published the most extensive data on robot application. The experience of companies in applying robots is widely distributed especially by JIRA, often with the help of MITI. Many factories where robots are being used serve as showrooms for the robot manufacturers. The Fanuc plant at Fuji and Yamazaki's FMS often have far more visitors then workers.

The robot exhibition in Tokyo in October 1981 attracted over 300,000 visitors. In addition, the Japanese translate and publish almost all available data on robots and robotic application all over the world. For many Japanese engineers, translation is unnecessary as they have a knowledge of English and sometimes other European languages. Several manufacturers of robots such as Nippon Electric Corporation have long trained their personell in English not only for sales purposes but to learn technology first hand.

No such translation program exists in the United States. The vast data on Japanese robotic applications is largely inaccessible to us. Without such knowledge, we may be making enormous efforts to reinvent the wheel.

7. Increasing R&D

Japan has made robots a top priority both for research and production. While the Japanese government assists greatly in providing market data thus indicating the areas of greatest profit, it does fund, directly and indirectly, R&D projects. The main support for R&D rests with the activities of companies themselves. The large companies, in particular, have been willing to assign significant numbers of trained engineers and technicians for robot research. Yet, it should be stressed that at least in the area of innovativeness and refinement in robotics, the Japanese have not shown any particular superiority. The SCARA robot may, however, be an indication of things to come. Japanese strength, however, still rests on the vast application experience it has been accumulating.

8. Exports

The Japanese expect that Western Europe and the U.S., as well as Eastern Europe, will make strong efforts to increase worker productivity. These "reindustrialization" programs will necessarily involve increased use of industrial robots and Japan plans to exportthem. While exports of robots were less than 2% in 1980, the Japanese expect that in 1985 and 1990, exports will constitute about 20% of production. The Japanese have been extremely active in the past year in establishing distribution networks in the U.S. and especially Europe.

A list of American companies importing or licensing Japanese robots include the following:

United States	Japan
General Electric	Hitachi
Westinghouse	(Mitsubishi Electric (Komatsu
IBM	Sankyo Seiki
Hobart Bros.	Yaskawa
Automatix	Hitachi
Admiral Equipment	Yaskawa
GCA	Dai Nichi Kiko
GM (joint venture)	Fujitsu Fanuc
Advanced Robotics	Nachi Fujikoshi
Machine Intelligence Corp. (MIC)	Yaskawa Electric

Two American companies have license agreements with Japanese firms:

Unimation	Kawasaki
Prab Robots	Murata Machinery

Some reciprocal interchange should be noted. MIC will supply Yaskawa with visual sensory devices and GM will contribute its painting robot to the joint venture with Fanuc. Kawasaki has provided Unimation with some new products and techniques but Unimation has clearly exercised technological leadership. IBM will purchase Sankyo Seiki robots but IBM will use its own language and control devices instead of Sankyo's language, SERF.

The Japanese attitude is expressed in the following view of Machida of the Long Term Credit Bank: "The industrial robots presently in use are, technologically speaking, still in their infancy.During the 1980's , they will mature from boyhood to the young adult stage. At present, Japan is the number one country qualified to be the parent of this child".

Accepting the challenge of Japan's lack of innovativeness and creativity, Machida wrote "It has been said that Japan cannot be victorious in the pioneer technology which is producing sophisticated knowledge intensive products because we do not possess high creativity. However, the expanding exports of Japanese intelligent robots will soon bear testimony to the fact of our international competitive strength not only in improvement technology and application technology but in pioneer technology as well."

APPENDIX I

Definitions of Industrial Robots

It may be argued that Japanese data on robots is confusing to Americans because of a difference in definitions. The Electric Machinery Law of 1971 in Japan defined an industrial robot as an all purpose machine, equipped with a memory device, and a terminal device (for holding things) and capable of rotation and of replacing human labor by automatic performance of movements. JIRA classifies industrial robots by the method of input information and teaching as follows:

1) manual manipulator--a manipulator that is worked by an operator.

2) fixed sequence robot--a manipulator which repetitively performs successive steps of a given operation according to a predetermined sequence, condition, and position, and whose set information cannot be easily changed. **This is considered a "dedicated" machine in the U.S.**

3) variable sequence robot--a manipulator which repetitively performs successive steps of a given operation according to a predetermined sequence, condition, and position, and whose set information can be easily changed. **In U.S. called a non-servo robot, pick-and-place or a bang-bang robot.**

4) playback robot--a manipulator which can produce from memory, operations originally executed under human control. A human operator initially operates the robot in order to input instructions. All the information relevant to the operations (sequence, conditions, and positions) is put in memory. When needed, this information is recalled (or played back, hence, its name) and the operations are repetitively executed automatically from memory. **Equivalent to the U.S. term "programmable robot".**

5) NC (numerical control) robot--a manipulator that can perform a given task according to the sequence, conditions and position, as commanded via numerical data. The software used for these robots include punched tapes, cards, and digital switches. This robot has the same control mode as an N.C. machine. **Equivalent to U.S. term "computerized" robot.**

6) intelligent robot--this robot with sensory perception (visual and/or tactile) can detect changes by itself in the work environment or work condition and, by its own decision-making faculty, proceed with its operation accordingly. **Sometimes called a sensory robot in the U.S.**

I have used three different robot definitions:

(1) "Robots by Japanese Definition"--all 6 classes

(2) "Robots by U.S. Definition"--classes 3,4,5,6

(3) "Sophisticated Robots"--classes 4,5,6

The American Robot Industry Association (RIA) defines a robot as "a manipulator designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks." Thus, the U.S. definition of robots eliminates the manual manipulators and fixed sequence machines.

APPENDIX II

Industrial Robot Production

Industrial Robot Production Value

Year	¥ Billion	$ Million
1968	.4	
1969	1.5	
1970	4.9	
1971	4.3	
1972	6.1	
1973	9.3	
1974	11.4	
1975	11.1	
1976	14.1	
1977	21.6	
1978	27.3	
1979	42.4	
1980	78.4	356
1981E	120-130	455-591
1985E	290-500	1,318-2,273
1990E	520-1000	2,364-4,545

**Exchange Rate: ¥ 220 = $ 1.00

Source: JIRA
Lower estimates are JIRA
Higher estimates calculated by P. Aron

It should be noted that JIRA has constantly underestimated future production.

1979 Estimate by JIRA - ¥36 Billion
1979 Actual shipments ¥42.4 Billion (17.8% higher than estimate)
1980 Original estimate by JIRA - ¥43 Billion
Revised estimate by JIRA - ¥65 Billion
Actual shipments - ¥ 784 Billion
(82.3% above original estimate and 20.6% above the revised estimate)
1981 JIRA's original estimate was ¥100 Billion
1985 JIRA's original estimate was ¥240-300 Billion
1990 JIRA's original estimate was ¥450-600 Billion issued in 1980.

Paul Aron's estimates are detailed in the Paul Aron Report #25 issued 7/28/81 and published by the Office of Technology Assessment in its Social Impacts of Robotics.

JIRA's most recent estimates annually are as follows:

	Billion ¥
1981	120
1982	130
1983	180
1984	230
1985	290

Production of Robots by Units

	Annual	Cumulative	U.S. definition
1968	200	200	
1969	400	600	
1970	1700	2300	
1971	1300	3600	
1972	1700	5300	
1973	2500	7800	
1974	4200	12000	
1975	4400	16400	
1976	7200	23600	
1977	8600	32200	992
1978	10100	42300	1438
1979	14500	56800	2763
1930	19900	76700	4493
1981E	25,000-30,000		8,000-9,000

Source - JIRA
Estimate: Paul Aron

Shipments of Industrial Robots - 1979

Type	Units	Value (¥ Million)
1 Manual Manipulator	1,051	2,100
2 Fixed Sequence Robot	10,721	19,990
3 Variable Sequence Robot	1,224	7,700
4 Playback Robot	662	7,200
5 NC Robot	89	1,700
6 Intelligent Robot	788	3,800
	14,535 units	42,400

Japan-Shipments of Industrial Robots [illegible]-1980

Units	¥ million
1,942	2,803
13,438	23,296
1,343	9,522
2,027	15,785
992	21,795
131	2,160

Industrial Robots in Japan

Share in Total Shipments (By Value)

	1977	1978	1979	1980	1981E
1	10	5	5	4	2
2	47	46	47	31	25
3	10	20	18	12	9
4	20	17	17	21	19
5	--	1	4	29	29
6	13	11	9	3	16

Sophisticated robots (categories 4,5,6) are clearly increasing - 53% of total value in 1980 compared to 33% in 1977. It should be noted that the intelligent robots (category 6) did not grow as fast as the playback on programmable robots and the computerized robots (category 4 and 5).

APPENDIX III

SOCIO-ECONOMIC IMPACT OF INDUSTRIAL ROBOTS

This section expresses the Japanese views on this topic and is greatly indebted to Mr. Yonemoto of JIRA, Japan's most prominent authority on this subject. Industrial robots have three major characteristics which, in large measure, determine their socio-economic impact.

1) Industrial robots,unlike special purpose automated machines, are programmable, and, as a consequence, are both flexible and versatile. A robot's movements may be altered merely by changing its program.

2) Industrial robots can perform beyond the physical and mechanical abilities of humans. They do not tire from long and continuous hours of work in an environment which may be uncomfortable, if not hazardous to humans. (They require no breaks to overcome fatigue or to meet personal needs).

3) Industrial robots perform with a high fidelity and accuracy in compliance with the instructions which they receive from man.

As a result of their versatility, super-human capability, and high fidelity to programming, industrial robots have changed in many ways the production scene in which they are employed.

1. Automation of Multi-Product Small Batch and Mixed-Flow-Production Line.

The flexibility and versatility of industrial robots makes possible the automation of multi-product small batch and mixed-flow-line production. The special purpose automated machine is restricted to limited model mass production. Recently, consumer demand has become increasingly diversified to the point where according to Japanese estimates, fully 80% of mechanized industry's products are manufactured in a moderate-to-low volume of output. Thus, the nature of contemporary consumer demand and particularly Japan's desire to accomodate a wide diversity of export requirements necessitated and encouraged the use of industrial robots.

2. Ease of Phasing in Product Design Modification and Model Changeover.

A complete changeover or even a modification in a product model often require changing or at least radically rebuilding a special purpose automated machine. Where an industrial robot is used instead, a mere change in program is required. As the product life cycle shortens, the flexibility and versatility of industrial robots becomes increasingly advantageous.

3. Improved Operating Ratio and Increased Operating Time.

Unlike men, industrial robots can operate on a 24 hour basis and therefore, the machines, they service can also operate on a 24 hour basis. Furthermore, industrial robots are capable of performing functions at a high speed which exceed human limitations.

4. Ability to Withstand Severe Working Conditions.

The industrial robot can work in an environment which is adverse to humans. Human beings require a host of conditions to make the working atmosphere both pleasant and safe-ventilation, proper lighting, air conditioning, or at least temperature control, and a variety of safety devices and conditions.

5. Ability to Execute Proper and Accurate Motions and the Ability to Cope Elastically with Changing Production Volume.

The sustained stability of industrial robot operation--their ability to work continuously and accurately faithful to their man-given instructions--eliminates slumps and spurts and provides a smoother production flow. This ability also enables increased production demands to be met effectively.

6. Change in Nature of Production System.

To the Japanese the introduction of industrial robots means a change in the production system. In the typical traditional mass production line the machine determines the activity of the operators--something pointedly satirized in Chaplin's famous film, "Modern Times". The operator programs the industrial robot and therefore, the human dominates the system. According to the Japanese, the industrial robot reduced psychological resistance to the conveyor system and thus permitted its more effective use. They believe that human satisfaction derived from the human control over the robot and this attitude led to qualitative improvement in labor.

7. Creation of New Technologies.

The characteristics of the industrial robots--combined with the change in the production system to a man-dominated robot-machine system led to the creation of completely new technologies and to their application in exploiting oceanic resources and in increasing utilization of nuclear energy. Robot applications to health, household, and cleaning duties have also been forecast.

The wide socio-economic impacts of the application of industrial robots expected by the Japanese roboticists has begun to be evident.

1. Improvement of Productivity.

The automation of small-batch and multi-product mixed-flow line production saved man-hours and reduced in-process and accumulated inventory. The improved operating ratio and increased operating time also reduced man-hours. The relative ease with which an industrial robot could be fit for a product design changed saved the time usually required for retooling. The more effective use of the conveyor system made possible by the industrial robot, also contributed to enhanced productivity.

2. Stability and Improvement in Product Quality.

The super-human capacities of the industrial robots and their fidelity to human instruction led to a uniformity of products and hence made possible the stability and improvement of product quality. By working 24 hours the industrial robot eliminated the incidence of inferior or defective products which often occur during factory start-up operations. The quality variations which result from long hours or the differing abilities of operators were eliminated.

3. Improvement in Production Management.

Production management has improved for several reasons:

a) Reduction of inventory and in-process products as a result of automation of small-batch and multi-product mixed-flow-line-production.

b) Reduction in set-up time and elimination of retooling the production line.

c) The durability and accuracy of industrial robots facilitated production planning.

d) Industrial robots reacting more elastically to production volume change reduced problems of manpower reallocation.

e) Industrial robots have helped to improve the quality of work life and led to greater employment stability. In addition, they have contributed to overcoming the skilled manpower shortage in such areas as welding and painting.

4. "Humanization" of Working Life.

a) Industrial robots released humans from hazardous and unhealthy working conditions preventing accidents and occupational diseases.

b) Industrial robots released humans from monotonous work and thus reduced psychological stress.

c) The man-robot-machine production system eliminated the psychological resistance to the conveyor system, and improved labor quality and human satisfactions from the human control of robots. Such a system corresponded better to a more highly educated and aging society. In recent years, Japan's society has witnessed a growing shift from blue-collar to white-collar occupations and the industrial robot enables corporations to accomodate to this trend. Human resources liberated from adverse work environments and from monotonous repetitive manual jobs are rechanneled into more intellectually demanding robot operations and maintenance positions. For example, manual wire bonding of IC's require the fatiguing performance of monotonous, repetitive tasks under a microscope, and a training period of 4 - 5 months. The industrial robot reduces the training period to 15 minutes and eliminates the fatiguing manual operation.

Robot utilization makes possible greater employment opportunity for the infirm, elderly and female work force in industries where heavy and continuous loading/unloading or carrying a heavy welding gun were required. The "humanization" or work life contributed to employment stability, reducing absences from work.

5. Resource Conservation.

Industrial robots contributed to conservation of resources, a high priority factor especially since the oil crisis of 1973. These savings were achieved in a variety of ways:

a) The robot saved material-the paint spraying robot, for example, used 20-30% less than the manual painters in many operations.

b) The ease of accomodating the robot to product design changes reduced investment in purchasing and/or rebuilding equipment.

c) The reduced defective ratio saved resources.

d) The industrial robot, by working in unpleasant environment, reduced the energy consumption of air conditioning, ventilation, lighting, etc.

d) By its ability to operate on one, two or three shifts, the industrial robot resulted in reducing investment.

Mr. GORE. Thank you very much for getting us off to a good and stimulating start.

Our second witness is Mr. Joji Arai, manager of the U.S. Liaison Office with the Japan Productivity Center.

Mr. ARAI. Thank you very much, Mr. Chairman, distinguished members of the committee.

Japan was first exposed to robotic technology in 1969 with the import of the Unimate and Versatran robots from the United States. At that time, the mean time between failure of robots was 250 hours and the cost was around $50,000, hardly justifying their use in the industrial environment. However, the booming economy and a shortage of labor prompted the Japanese to focus their attention on the potentials of robots.

In the beginning, robots were used in the second shift of sublines of automobile manufacturing, then expanded into machining, assembly, casting, plastic molding operations of the automobile industry as well as electrical applicances, plastic and metal fabricating industries as the MTBF was extended to 2,000 to 2,500 hours. In the meantime, the wage rate in Japan tripled while the price tags of robots remained the same.

Not only did the use of robots become economical but also the reduction of the manufacturing cost and improvement in quality and performance accelerated the application in a wide range of the manufacturing industry. There are about 140 Japanese manufacturers of various types of robots with an annual sale of $400 million. The 11th Domestic Industrial Robot Symposium, which was held in Tokyo in October 1981, attracted 700 robot researchers and engineers from 27 countries. The Robot Show, which was concurrently held for a 5-day period, attracted 328,000 people.

The tax incentives and the establishment of a robot leasing company and the realization by management and labor unions that robots relieve men of repetitive and dangerous work triggered a geometric increase in the number of robots on the industrial scene starting in 1978. In the period between 1978 and 1979, 23,000 robots were manufactured, and it is estimated that sales will increase to $1.4 billion in 1985 and $2.6 billion in 1990.

Currently 38 percent of the output is delivered to the automobile industry, 18 percent for electrical machinery and applicances, 11 percent for plastics, 8 percent for fabrication, 4 percent for steel, and 3 percent for machine tools and metal fabricating machinery industries. Of the total number of robots delivered in the last 2 years, the largest number is used for plastic molding. In declining order, other prevalent uses were in assembly, machining, stamping, die-casting, spot welding and arch welding.

It is estimated that the annual output of manipulators and robots will increase from the current level of 20,000 units to 50,000 in 1985 and 85,000 in 1990, with the largest increase in intelligent robots at an annual rate of between 30 to 55 percent between 1985 and a 25 percent increase between 1985 and 1990.

There is a difference in the definition of robots between the United States and Japan. Japanese define robots as things whose functions cover various movements with a high degree of freedom in three dimensional space. This includes manual manipulators, fixed sequence robots, variable sequence, playback, numerical controlled and intelligent robots. The latter three categories of devices fall into the generally accepted definition of a robot in the United States. In value this represents approximately 30 percent of the total Japanese output. Still, close to 75 percent of the entire robot population is located in Japan. Currently intelligent robots represent only about 10 pecent of the total output.

Although Japan has the largest installation of robotic systems she is not necessarily in a superior position in the technological development of sophisticated intelligent robots. There are about 90 institutions conducting research programs related to industrial robots with an annual budget of between $1.700 and $14,000 per researcher which is considerably smaller than the research funds available to their American and European counterparts.

The factor that is giving Japanese the edge in R&D and practical application is the coordinated effort among the users, manufacturers, research institutions and the government. This can be seen in the Ministry of International Trade and Industry initiated $65 million flexible manufacturing complex with laser application, which was started in 1977 and is expected to be concluded in 1983. Each FMC cell includes five computer controller automatic processes including fabricating of parts with the use of flexible dies, machining treating and machining by laser, assembly by robots and automatic inspection. This project triggered the accelerated improvement in robotic research being conducted by academic institutions and private companies.

The development of reliable industrial robots enabled many companies to institute flexible manufacturing systems consisting of many machining cells made up from CNC machine tools, industrial robots and monitors. Work pieces are transferred from these cells by unmanned carriers operated by computers. The FMS enabled many companies to minimize inventories reduce the lot size and labor input, maximize equipment utilization and flexibility. Many discovered that they could reduce labor input down to one-fifth to one-tenth as compared with traditional operations.

The FMS is now proliferating into the small business sector, and we find many small factories with a machining center, NC machine tools and a few robots running a highly efficient operation, overcoming the reported disadvantage of subcontractors.

Japan's onslaught to proliferate robotic systems will have a serious impact on developing countries, which up to now were able to supply labor intensive parts, components and finished products to the markets in the advanced countries because of their labor cost advantage. The highly efficient FMS enables advanced countries to manufacture those products without relying upon inexpensive labor. This will also place many American and European multinational corporations, which opted to move operations to offshore for cost consideration, in a disadvantageous position.

The unplanned proliferation of FMS in the manufacturing sector will undoubtedly widen a gap between the advanced and developing countries forcing a confrontation with the Third World.

Another area where a serious impact of robotic development can be seen is in the labor force. Of the total labor force in Japan, 34 percent are employed by the secondary sector. Of the total industrial workers approximately 20 percent are in the machining and material fabrication, which is susceptible to the influence of the current technological level of the playback and numerically controlled robots and sequence robots. An immediate impact will be felt by this sector of workers, as we are already seeing experimental and prototype unmanned plants being run efficiently with one-fifth and one-tenth of the labor force traditionally required.

Since 1975 we have seen the manufacturing sector, consisting of companies employing more than 30 people, lose 1 percent of their labor force every year. The service sector of the same category of employers increased faster than the former. Japan was able to make the transition without a displacement problem because her annual population increase is about 1.1 percent with only 0.7 percent increase in the labor force as more and more young people stay in academic institutions longer.

The geometric increase in the output of robots of all forms from 20,000 a year in 1980 to 85,000 in 1990 may not give Japan sufficient time to make the necessary transition from a manufacturing oriented society to a knowledge intensive service oriented society. The only answer Japan has at the moment is that management, labor, and government should coordinate their efforts to make proper adjustments to cope with the emerging changes. Perhaps the experiences of Japan in the next decade will indicate to other countries what should and should not be done in making these changes.

On the corporate level, companies moving into FMS are setting aside 3 months to 2 years to retrain displaced workers so that they may move to other jobs within the same company. As a matter of fact, a recent Ministry of Labor study showed that while there was an overall decline in employment in the manufacturing sector, 48.4 percent of those which introduced automation reported an increase in employment, as compared with 42.3 percent of those who had not. Those companies that reported the increase in employment as a result of the introduction of the systems attributed it to, one, an increase in orders—68.1 percent, two, an expansion of business—31.5 percent, and three, new skill requirements—29.8 percent. It is estimated that within the next 10 years there will be an accelerated increase in employment in R&D and sales while the administrative and manufacturing departments will become smaller.

However, this may not be sufficient to take care of the potentially displaced as the FMS spreads into many industries and advanced playback robots replace auto-loaders and single-purpose automatic machines in the machining and material fabricating industries. Further the emergence of intelligent robots with their wide application in assembly operations will affect twice as many people as those in machining and fabricating industries.

One may argue that a general apprehension that industrial robots would displace a large number of workers is without merit because computers, once feared as a threat to workers, actually increased employment opportunities by creating new jobs. The industrial robots and their application as integral parts of FMS may give rise to demands for new products, services and skills. The Japanese experience showed that the application of the systems increased demands for software specialists and sales engineers.

Japan is endeavoring to develop the sophisticated FMS system so that she will be able to increase her output and will be able to survive in the global economy in competition with advanced countries as well as the developing countries taking advantage of the cost reduction possible with the effective application of the system.

Thank you.

[The prepared statement of Mr. Arai follows:]

STATEMENT OF JOJI ARAI, MANAGER, U.S. OFFICE, JAPAN PRODUCTIVITY CENTER

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The geometric increase in the output of robots of all forms from 20,000 a year in 1980 to 85,000 in 1990 may not give Japan sufficient time to make the necessary transition from a manufacturing oriented society to a knowledge in~~s~~tensive service oriented society. The only answer Japan has at the moment is that management, labor and government should coordinate their effort to make proper adjustments to cope with the emerging changes. Perhaps the experiences of Japan in the next decade will indicate to other countries what should and should not be done in making these changes.

On the corporate level, companies~~,~~ moving into FMS are setting aside three months to two years to retrain displaced workers so that they may move to other jobs within the same company. As a matter of fact, a recent Ministry of Labor study showed that while there was an overall decline in employment in the manufacturing sector, 48.4% of those which introduced automation reported an increase in employment, as compared with 42.3% of those who had not. Those companies that reported the increase in employment as a result of the introduction of the systems attributed it to 1.) an increase in orders (68.1%), 2.) an expansion of business (31.5%) and 3.) new skill requirements (29.8%). It is estimated that within the next ten years there will be an accelerated increase in employment in R & D and sales while the administrative and manufacturing departments will become smaller.

However, this may not be sufficient to take care of the potentially displaced as the FMS spreads into many industries and advanced playback robots replace auto-loaders and single-purpose automatic machines in the machining and material fabricating industries. Further the emergence of intelligent robots with their wide application in assembly operations will affect twice as many people as those in machining and fabricating industries.

One may argue that a general apprehension that industrial robots would displace a large number of workers is without merit because computers, once feared as a threat to workers, actually increased employment opportunites by creating new jobs. The industrial robots and their application as integral parts of FMS may give rise to demands for new products, services and skills. The Japanese experiece showed that the application of the systems increased demands for software specialists and sales engineers.

Mr. GORE. Thank you very much, excellent testimony.

Let me ask a couple of questions, then I want to ask our expert discussants to ask a few. First of all, Mr. Aron, I would like you to help me develop a better understanding of what the likely impact on industrial society as a whole will be as a result of this trend. Some observers predict that an extremely high percentage of jobs that are variously described as low wage jobs, unskilled jobs, assembly jobs and the like, that a high percentage of those jobs will be performed by robots of one kind or another within two or three decades, and that as a result, millions of people now so employed will have to find other employment.

What do you think about the magnitude of this impact?

Mr. ARON. Well, I have used a calculation that at the maximum one robot is equal to six human beings. One robot will work 24 hours a day, it will do the work of two people per shift. That is a very rough rule of thumb.

Mr. GORE. All right.

Mr. ARON. If we are talking about the number of robots to be installed in America by 1985 as 15,000, then we are talking about 90,000 people being displaced, with an unemployment figure, I am not minimizing that, 90,000 is not a very significant number.

In other words, there is not very much of an immediate problem. I think you are quite correct that there is a long-run problem. So we have time to work it out.

Mr. GORE. Wait just a moment now. If 90,000—your calculation assumes that the only robots displacing American workers will be those installed here in the United States. If there are another 50,000 installed in the Philippines, Brazil, Taiwan, et cetera, and as a result American workers are unable to compete, then the same effect, I mean they are still unemployed, or they are still looking for another way to make a living.

Mr. ARON. I think you are quite correct. Let me point out that the problem facing the United States is really taking its labor force, which exists today, which is an excellent labor force, often quite educated, knowledgeable and certainly trainable, and training them for the occupations of the future, not the occupations of the past. I will just give you one number.

In the case of Japan, there are 130,000 people involved in what we could broadly call information processing in 1980—130,000. They expect that by 1985 it will be 796,000, an increase of 666,000 jobs. If you take the number that I use, 100,000 robots to be introduced in Japan by 1985, you will see that the 600,000 jobs they displace could ideally be filled by the need for information processors.

Mr. GORE. Yes.

Mr. ARON. So I think the problem is there is no reason to try to preserve, in my opinion, jobs which are no longer meaningful any more than it was meaningful to preserve the horse and buggy. But there are other jobs available. We have to train for them.

Mr. GORE. I don't wish to debate the point that other jobs will be created, nor do I wish to create the argument that the number of other jobs created may nearly equal those eliminated. You can argue the other side of that, and I don't know what the correct answer to that is. What I am trying to do at this point is get a better fix for the magnitude of the impact. Not to characterize it, but to try to determine how big the impact will be and how soon it will occur.

Business Week magazine reported in its issue on artificial intelligence that robots and closely related developments would cost by the year 2010, which is a little different timeframe than the one you are using, 25 million of the 28 million manufacturing jobs in the United States. Do you think that is a wild estimate, or one that is close to the mark?

Mr. ARON. I think it is high. But I think there is no question at all that we are talking about millions of jobs ultimately when we are talking about introducing something like 1 million robots. Here we are talking about 15,000. It is quite a difference in scale between 15,000 and 1 million.

Mr. GORE. Yes.

Mr. ARON. I think what I would want so much to stress is that we have the time now to prepare for the future. In other words, if we recognize early enough the direction the future will take and prepare people for the future, we should not wait to allow the problems to occur and say now what do we do about it.

Mr. GORE. That is one of the reasons we are having this hearing. I couldn't agree with you more. In order to get some sort of goal alinement in this country, you have to describe what the future looks like in general terms. I take it the thrust of your testimony is whatever the future looks like, robots will play a great role in shaping them.

Would you agree, Mr. Arai?

Mr. ARAI. Yes, I do agree. However, I would like to point out the fact that while the tendency in the United States is to argue the impact of a robot on the employment scene, I think we should consider a robot as just an integral part of the total system, which will be coming into the industrial scene in the United States as well as the rest of the world very shortly.

Actually, we are seeing the combination of robot systems together with the machining centers, numerically controlled machines, loaders, and automatic warehouses. All that, automated system coming into the plant, replacing a large number of people at one time. We have experiences in some of the prototype operations in Japan in which the traditional 250-man operation was replaced by 12 men with use of the system. They only have a few robots. But a combination of those devices enables you to have tremendous reduction in labor input.

We should consider the impact of robots as an integral part of the introduction of such system into the industry. I am sure the world will have to come up with a very comprehensive retraining program and improvement in the public education system to cope with those possible changes in society.

Mr. GORE. I would certainly agree with you. It seems to me that the countries that most successfully and quickly adopt robots will have an increasing advantage in world trade?

Mr. ARAI. Obviously the implementation of the flexible manufacturing system in addition to regular mass production system enables a country to take advantage of a cost reduction, because those systems certainly can replace cheap labor and the improvement in the quality gives the country an advantage in the marketplace.

Also I believe the advantage comes from the societal structure in which you can create increasing number of the service sector functions which obviously Europe has difficulty in creating as compared to the United States and Japan.

Mr. **Gore**. Mr. Aron, did you want to comment on that? To rephrase the question slightly, isn't it true that there are going to be enormous pressures driving countries competing with each other to install robots more quickly, and that the implications are not just within one nation's boundaries, but that these pressures and this dynamic is going to force, very likely will force a rapid worldwide adaptation to robotic manufacturing techniques? Isn't that fair to predict?

Mr. **Aron**. I think that is very fair. I would like to join with Arai in his view that when I talk about robots I am merely talking about the tip of the iceberg. We are really talking about new flexible manufacturing systems in which robots play a very important role, but it is not exclusively robot.

Mr. **Gore**. CADCAM.

Mr. **Aron**. CADCAM, we are talking about machining centers, numerical control of all types, unmanned carriers. I visited the plant Mr. Arai is talking about, the Yamazaki plant where six people on each shift are running a plant which, a total of 13 people in all because the plant works 24 hours a day, only at night there is no one in the plant except the watchman. One of the big questions was why the lights are on at night in the plant.

Mr. **Scheuer**. They told us they turned the lights off.

Mr. **Aron**. Right. They just gave the watchman a flashlight. Now I wanted to make one or two comments if I may. One, that the Japanese are trying very hard to recapture industries which they lost to the lower cost intensive labor countries surrounding them, like Hong Kong, Singapore, South Korea, and Taiwan. The form it is taking is the application of robots and flexible machining. We have two areas where they have been most active in research. One, the application of robots and flexible machining to shipbuilding. In other words, they are working very intensively to change the whole nature of shipbuilding so it becomes to a great extent a robot assembly type.

The second area is development of clothing manufacturing to move completely away from the handmade manufacturing so you can get a machine system a system, which will take the raw material at one end and what will come out of the other end will be the shirts, et cetera. We feel that the intensive investment in plant and equipment will enable them to meet their problem.

Mr. **Gore**. You put an individual customer's measurements in?

Mr. **Aron**. Well approximately. I don't think the batches are that small. I would like to make——

Mr. **Gore**. Some have predicted that the apparel industry will soon adopt such a technique.

Mr. **Aron**. It is possible. I would like to emphasize one thing. That is, I think the robots should be allowed to do the heavy work, the hard work, the inhuman work, and let the human beings do the creative work. I think we are being given a tremendous opportunity. Robots are enabling us to train people to participate as human beings, not as horses in production. To utilize their creative industry to solve problems, not just to repeat, as Charlie Chaplin did in "Modern Times," the movement of the wrenches constantly. It is an opportunity. I guess the very word crisis, which it is, in Japan has two symbols. It is the symbol for danger and the symbol for opportunity together, that is a crisis. We have emphasized the dangers but we also look at the opportunities.

Mr. GORE. The first creative opportunity is to figure out what we are going to do, what the people displaced are going to do. We are honored to have the chairman of Natural Resources Subcommittee, Congressman Jim Scheuer.

Mr. SCHEUER. Well, I am very happy to be here. I want to congratulate you, Mr. Chairman, on your initiative and imagination and leadership in holding this hearing. I had the honor to spend a couple of weeks in Japan last summer as a guest of the American and the Japan Productivity Foundation with Joji Arai being our key leader there in arranging for us to see so many interesting phenomena.

We did see the Amisaki works that you are talking about, Mr. Aron. They did tell us unmistakably and unequivocally that they did turn out the lights on that third shift. It was an amazing perspective. They did talk about robots taking over the jobs that were hot, heavy, hazardous and boring—I forget. What is the exact phrase, Joji?

Mr. ARAI. Simplistic, repetitive, boring, dangerous jobs.

Mr. SCHEUER. There were three H's as I remember. Hot, heavy, hazardous, boring.

There are some tremendously perplexing and challenging lessons for us to learn in looking at the Japanese experience with robots. There certainly are both of those characters you pointed out. It is a danger but it is also an opportunity. I think we have to do some sharp analysis of what is the underlying environment that has made Japan so receptive to robotics. And what differences we have between Japan and America and what we have to do, what spade work we have to do to clear the way for further introduction of robots and all the related high technology, because I agree with you, Mr. Chairman, if we don't do that, we are gradually being excluded, maybe not so gradually, being excluded from local competition in many of the areas we have traditionally thought we have been preeminent.

Mr. GORE. Will the gentleman yield on that point.

Mr. SCHEUER. Of course.

Mr. GORE. The thrust of Mr. Arai's testimony, part of the thrust of his testimony, was that the success of Japan's application of robots technology has been facilitated by the guarantee to the workers in the plants where they are installed that they are not going to lose their jobs, and encouragement of the employees to come up with better applications to improve the use of robots. In this country, where the subject evokes fear and concern, we simply have to find a way to make that or a similar guarantee, whether it is in the same precise location, or whether it is a meaningful, believable guarantee of quality employment elsewhere.

I think that is one of the keys to this country participating in what some observers have called the next industrial revolution.

Mr. SCHEUER. I quite agree with you. You have two phenomena at work in Japan. One, the widespread existence of, in effect, lifetime employment. I think about 40 percent of Japan industrial workers and much larger percentage of industrial workers in major sophisticated industries enjoy lifetime employment. That has two consequences. It means that the employees and labor unions identify more with the corporation, because with lifetime employment, there is a widespread consensus that they are all paddling in the same boat, and that the well-being of the corporation is really directly related to the well-being of the employees. So there is less of a proclivity or less of an inclination to be confrontational on any subject. So that is one advantage.

The next great advantage they have is that they are dealing with a substantially, 100 percent literate work force. So that means that each worker who is working on an assembly line basically has the potential of doing something more sophisticated and more remunerative, and of having his skills upgraded. So the corollary to that is that not only is the worker identifying his future with the corporation, but because the corporation knows that if they spend time and money in educating the worker further and enhancing his skills, that he is not likely to walk across the street and go to work for a competitor, the corporations same willing to spend large amounts of money and time in retraining and upgrading that worker's skills, maybe 6 months or 1 year in universities and technical skills both in Japan and abroad.

They have an extraordinary program of upgrading workers' skills so a production line worker becomes a computer operator or programer, or some other job description. He can fit another job description and meet the requirements of another job that is far more sophisticated and offers greater career potential and financial potential to him than the job from which he was displaced.

Now in the United States we don't quite have that situation. Many of our workers do not have the literacy skills, the numeracy skills that the overwhelming majority of Japanese workers do. Therefore, even if the corporations were willing to spend the time and money, you don't have the potential in many of these cases to upgrade the workers' skills.

I think the corollary to that is, not only do we have to work at making our union, our labor-management relations less confrontational, and trying to create over the long pull the consensus that we are all in this boat together, but going right back to the elementary and secondary education system in this country and remedial education system, perhaps on the job, we have got to position the average American worker on a production line or in a service industry who may be displaced by robotization or something like that, we have got to equip that worker to handle other more challenging, more demanding jobs. That just, I mean if anybody needed to emphasize the urgency of our creating a 100 percent literate and productive work force, this just puts the whipped cream on the cake.

In my opinion there is no more important national priority than making sure that every young person in America, boy or girl, man or woman, is equipped to read, write, count, and function in a world where sophisticated skills, increasingly sophisticated skills, are becoming indispensable for almost any kind of employment. The day in America where a willing heart and strong back was sufficient to eke out a marginal existence are gone.

I just think that we need to consider that a top priority matter. Educating every young boy and girl in America so that they can function in an environment and in an economy that simply won't reward them, won't have a place for them unless they have reading, writing, and counting skills on the job.

I apologize for making a long speech, but in that several weeks I had with Joji in Japan he really primed me for this hearing. I apologize, and I look forward equally to hearing the next panels.

Mr. **Gore**. No, no, thank you very much. That is a very helpful improvement to the record.

Congressman Volkmer.

Mr. **Volkmer**. I have nothing.

Mr. **Gore**. We have three expert discussants that I want to invite to ask brief questions for this panel. If any of the members want to interrupt during this time, please feel free.

Dr. Sanderson, would you like to begin?

Dr. **Sanderson**. Certainly, Mr. Gore.

There was one point I think you made, and which was certainly made by our panel, that I would like to emphasize. That was the point that we are now dealing in a world economy.

Congressman Scheuer, you, have also emphasized the importance of the training and skills of the U.S. citizen. It is an area that we are very concerned about in terms of raising the literacy of the entire U.S. populace in the area of science, technology and thereby the U.S. ability to compete. But at the same time I think we have to realize that we have very few options in this matter because we are trading in an era where it is less expensive to move a finished car from Japan to the United States than it is to manufacture that car here in the United States. And therefore, we perhaps are moving more slowly than desirable, both in our laws and in management skills, in recognizing that we are competing in a global economy.

One of the questions which I would like to ask Mr. Aron particularly, is, you made a number of comparisons between the Japanese and attributed their success to differences in labor and management and the role of government. In the same perspective, and given the social differences which exist between our two countries, what would be your perception of the United States, that is our strong points and our weak points in introducing these technologies?

Mr. **Aron**. I think the first major strong point I would see in America is the technological innovativeness which pervades a great deal of American science and technology. I think there is no question in my mind that we are the technological leaders in this area. I think I made that statement in the testimony; you have to go beyond that leadership. I think in addition we have in place in America a very substantial educational system. We have universities which in many ways are far superior to universities that exist in Japan. The training of Americans is far better in the universities. Where the Japanese are able to advance is the training which they get after they leave the university.

So what I think we have to do is work toward a greater coordination between university and industry, between university and the Government. We have the structure in place for that. I think this is another great advantage; we don't take enough advantage of it. I think, too, that while we have the creativity, one thing that struck me in studying Japan, is that a great number of our people look for increasingly sophisticated ideas. They tend to minimize the Japanese contribution.

Now we have, for example, a very fine assembly robot in the United States called the Puma. The Japanese developed a less sophisticated robot called Scara. It had one less degree of freedom. However, the Scara cost half the price of a Puma. There are now operative in Japan several thousand Scaras. I don't know whether we have reached a 1,000, I don't know whether we have reached 100 with the Puma.

Mr. GORE. Excuse me. To clarify the record a degree of freedom is a degree within an arc?

Mr. ARON. Well, there are six degrees of freedom that are possible. Up and down, side to side, in and out for the arm. Then the same, basically the same movements for the wrist. So there are six degrees of freedom possible in a robot, because they have whether the robot has—different types construction.

The Japanese tend to have robots with far fewer axes. But what happens is, they study what job has to be done and they design to meet the job. The Matsushita robots coming out now are very simple robots but they meet the job. I think we have the ability to do the same thing if we redirected some of our energy here.

Mr. GORE. Toward application.

Mr. ARON. Toward application. I think we have to make much more meaningful the role of the manufacturing engineer. In an American university if you succeed in nothing else in engineering you became a manufacturing engineer. That is the bottom of the pile. That is a dreadful error because a great deal of the key lies there and we have to work on that area.

This is a much broader thing than the robot area we have to study, the role of the interest rate, the role of management fear, which is certainly being discussed today. If I recall correctly from the history books, we faced an enormous challenge in 1941. In 1941 we developed the largest productive machine the world has ever seen and became the arsenal of democracy. We developed production at a rate that was just incomprehensible. At the high point of World War II the Japanese production of automotive equipment per year at the highest point was 35,000 units. 35,000 units. So they were minimal compared to the us.

So we have the ability, it is a question of redirecting ourselves, of making certain structural changes, but I don't think there is—I think there is nothing within America that would prevent this from taking place.

Mr. GORE. Dr. Chern?

Dr. CHERN. Let me touch on one point which Mr. Arons has discussed. This will come up again in other panels. Namely, this idea of far too sophisticated machines. You are really talking here about the kinds of market strategies and what is available. One approach is to say the following. I really have a series of problems I want to solve, whereupon I begin to look for solutions to those problems. Those solutions may involve robots, they may not involve robots, depending upon what is available. It is true that by looking at problems you indeed try to use robots, you look at what incremental improvements are usually needed on the state of the art in order to solve those problems. That is a valid approach.

I think the statement here would be that that is a sort of application driven research. I think that is in reasonable shape. You make a point that it may not be in as good shape as one would like. And that I think is something one would have to talk about; namely, American corporate planning and implementation of robots.

But let me mention the other approach, because it will occur, also. That approach says the following: that we have machines called robots. They are relatively simple machines today. One looks at what is possible to build and one says why can not one recognize the limitations of what we have today? Those limitations define very sharply the kind of applications where one can use robots and the actual numbers that can be put into manufacturing.

Let us indeed try to develop new technologies. Let's really try to make improvements because if we do that, if we can make robots which are computer controlled, which have sophisticated senses, which allow them to be easily reprogramed, then those machines can be used for different kinds of tasks. I am not limited to a pick and place or repetitive task in some particular operation. So there are different market strategies that come in. Both have their place.

I think we will later see that the current status of robots are such that significant improvements are possible and those improvements will really open the field of application for the new generations of robots.

Mr. GORE. Do either of you want to comment on that briefly?

Mr. ARON. I would like to comment, if I may. I understand very well the point you make, and it is well made. My concern is this. That while we dedicate ourselves to finding more and more sophisticated and better robots, we find that larger and larger areas of manufacturing are being taken over by those people who use the existing equipment. By the time we have come to the marketplace with that new, finer equipment and so forth, the marketplace has already taken off, in the same way that some of our American firms look for a different method of producing the 64K dynamic random access memory. While they were playing with the 64K, the Japanese moved in and took 70 percent of the market. So that you may wait a little bit too long.

The other point I would like to make is this. We are devoting an enormous amount of time to developing robots that can pick up in a bin different objects, round, square, circular, and so forth. We have expensive robots that can sense this. I wonder how serious it is as an application. It is a wonderful problem technologically, but in an actual plant, does a worker get a boxful of assorted parts and say, "Here, pick out the one." Or does he get all ⅜-inch screws and say, "Here this is what you are using."

We are developing a wonderful machine but what practical application does it have to the manufacturing business?

In fact, we can take a $125,000 machine to sort stuff in a bin. We can pay a worker $20 an hour, $50 an hour and that worker, he or she will sort the bin much faster than the robot will ever do. So my concern is sure there are long term implications. I am not oblivious of those long-term implications. But I think if we just preoccupy ourselves with the long-term implications, we are going to lose in the short run and never be able to put into effect those long run refinements.

Mr. **Arai**. Our research indicates that while the large percentage of currently installed Japanese robotics systems are relatively primitive type, they are generally categorized as fixed sequence, variable sequence, manipulative type. However, we see the parallel development in the highly intelligent robot. And most of our research funds in the next 5, 10 years, will go into the development of very sophisticated robots.

As a matter of fact the forecasted growth of the intelligent robot is 50 percent per annum, as compared to 23, between 15 and 25 percent growth for the other primitive type of robot. Obviously, we are moving in that direction because we realize, one, the fact that the currently available robots only can be effectively utilized in the machining and metal material fabrication industry which only employs approximately 20 percent of industrial workers. The remaining 70 percent of the work in the manufacturing industries are in assembly operations.

The assembly operation can be only performed by highly sophisticated robots. Therefore, in the future the Japanese will concentrate their effort to develop sophisticated robots. But of course, with emphasis on combining of those technologies so that they can come up with the very sophisticated, the flexible manufacturing complex with possible application of laser beam.

Mr. **Gore**. Dr. Strauss.

Mr. **Strauss**. I would like to get back to the unemployment question for a moment. We have heard an estimate of how many people are employed due to the installation of one robot. But I would like to ask a question from the other point of view, seeing what has happened in the steel industry and automotive industry due to not automating fast enough. I wonder if we could have an estimate of how many people are unemployed due to not putting in a robot or flexible machining system, if you have any idea of that number in the United States, Japan, and Western Europe. That is, let us try and balance this. Which is greater, unemployment and displacement greater from not putting in automation, or from putting in automation?

Mr. **Arai**. In the last 5-year period the Japanese automobile industry reduced labor input by approximately 10 percent. That is, automation as well as installation of the new production system called stockless, or "Just-in-time" method, enabled the Japanese to reduce that much labor input in the automobile sector. However, during the same time they have increasing output of between 25 and 50 percent. On the contrary, in the United States you have seen the decline, total automobile output, from 12 million per annum down to 8.9, I believe, last year. And labor input, actually, displacement, occurred in the range of approximately 20 percent.

However, I do not believe that the whole 20 percent displacement or layoff by automobile industry in the United States resulted from the lack of the management enthusiasm to install automated systems at all. There is a combination of the factors that affected the decline of the automobile industry in the last few years in the United States. But certainly, that slower progress in installing the system contributed toward the decline of the industry.

Mr. GORE. I think Mr. Aron wanted to comment.

Mr. ARON. I thought that was an excellent question. I would say that we are paying far more for the failure to install the latest equipment in a whole series of industries than robots could possibly take away at this point. The steel industry is suffering by being noncompetitive. But the continuous casting process in Japan affects maybe 80 to 90 percent of steel being made in Japan. Continuous casting means a steel that has a yield of 90 percent, as against 70 percent. It means a steel which can be produced for far less. And we are plagued with an uncompetitive steel industry because for some reason the industry has not invested in new technologies, continuous casting, and so on.

I think it is two things. One, the failure to make the equipment investment in these areas. A second area is the lack of concern for quality. We have been so driven in American history to produce, and to produce the maximum, we are trying to build inspection into the product after the product is made. The key really lies in making the product right in the first place. I do not know what percentage of automobiles are reworked, but I would guess, based upon conversations I have had with people that as many as 30 percent of the finished automobiles have to go for rework within the factory. That means that a great number of workers in the factory are dedicating themselves to reworking, and that is increasing tremendously the cost of labor in the plant. I think we have two elements involved here.

Mr. SCHEUER. Will the witness yield at that point for a brief question?

Mr. ARON. Please.

Mr. SCHEUER. Is that 30 percent of reworked automobiles a result of workers not doing the job properly on the line, or machines not being accurately engineered and the machines not doing the work properly?

Mr. ARON. The worker will tell you when he sees something wrong he is told by the foreman, "Your job is to build automobiles, not inspect them." In Japan every worker is an inspector. Not only is he an inspector, but in the automobile plants that you have been in you may see there is a red button or cord. The worker can stop the production line himself without the authority of the foreman because he does not like what is going through the line.

In the United States I read in the Wall Street Journal of a Ford plant where they were not able to close the doors on a car. The car continued to be produced. They got to the plant chief to get his approval to stop the line, and he had to call up Detroit to get an approval to stop the line because they could not close the doors. I do not know because the article did not tell you whether the people were in Detroit to tell him you may stop the line, but I think these are two elements we have to consider. Equipment—of course they are very much related, because the high quality of a great deal of Japanese production lies not only in the worker, but also lies in the fact that you have automated equipment which is making it possible to develop a much higher quality product.

Mr. GORE. I might say we have General Motors on the next panel. We will ask them to respond on behalf of Ford.

Dr. Sanderson, you wanted to make a comment?

Dr. SANDERSON. Yes. We were talking about the loss of jobs. I saw one statistic on this about a year ago. That came out of an area mentioned earlier, namely, the men's tailored clothing industry. The analysis which I saw indicated that at present, approximately 20 percent of men's tailored clothing, the suits we are wearing, are manufactured offshore. The predictions based on the relative labor cost and introduction of improved production overseas were that unless U.S. production techniques changed, within 5 years we would lose over 50 percent of the market, with the resulting displacement of a significant number of U.S. workers.

That has led perhaps to a bright point. There have been a number of the companies in that industry, along with some representatives of the labor union, who are actively seeking to introduce new technology into that industry. We have worked with them, to identify some areas of new technology. So the labor picture is more mixed than one would think in terms of objection to the introduction of automation, and I think that an increased awareness is developing in many areas that we have no viable alternative.

Mr. GORE. Well, thank you very much. We are going to have to move along, because we have so many witnesses. I want to thank you all for getting us off to a good start. We could spend all day asking you questions. But in the interest of time and because we have many witnesses today, we will be forced to move on. Thank you both very, very much.

Mr. ARON. Thank you very much, Mr. Chairman.

Mr. GORE. I would like to call our next panel, Mr. Michael Radeke, vice president and general manager of the Industrial Robot Division of Cincinnati Millicron in Lebanon, Ohio; Mr. Charles Rosen, chairman and chief scientist of Machine Intelligence, Inc., in Sunnyvale, Calif.; and Mr. Lothar Rossol, assistant department head of computer science of GM Research Laboratories, General Motors Research Corp. operations working here in Washington. He is accompanied by Richard Beecher, manager of robotics, perception and team study of the manufacturing development staff at General Motors.

Gentlemen, we are delighted to have you here with us.

Mr. Radeke, we will begin with you. Without objection, the entire text of the prepared statements of all our witnesses will be included in full in the record.

STATEMENTS OF MICHAEL RADEKE, VICE PRESIDENT AND GENERAL MANAGER, INDUSTRIAL ROBOT DIVISION, CINCINNATI MILLICRON; CHARLES ROSEN, PRESIDENT, MACHINE INTELLIGENCE, INC.; AND LOTHAR ROSSOL, ASSISTANT DEPARTMENT HEAD OF COMPUTER SCIENCE, GM RESEARCH LABORATORIES, GENERAL MOTORS CORP., ACCOMPANIED BY RICHARD BEECHER, MANAGER OF ROBOTICS, PERCEPTION AND TEAM STUDY, MANUFACTURING DEVELOPMENT STAFF

Mr. Radeke. Thank you, Mr. Chairman. I think when we look at robotics it represents many different aspects of technology. Certainly the mechanism, electronics and computer softwear that surround the robot are very high-technology areas. Additionally we are seeing daily introduction of sensors and electronics to interpret what is going on around the robot and redirect its activities. The third area is process oriented, technology that deals with how robots are used.

In looking at the panel that is going to appear today, I feel very comfortable that others will cover the first two points. Certainly from our company viewpoint we have been very active in the research and development of technology in those areas. But the point I would like to concentrate on is one covered by Paul Aron, because I think it is the key to the success of the United States overall in manufacturing. That is in the systems area, the application of a robot to do a task. After all, robots are a tool. They do nothing by themselves. They only do work when applied to a task. It is the application to that task that is the crucial and critical area that I believe the United States is having some difficulties in.

Could I please have the film now to illustrate some of the applications of robots. By the way, I apologize for the commercial nature of the film, but it was developed by our marketing group.

[Film shown.]

Mr. Radeke. Thank you.

The significance of this film is that a single tool, an industrial robot, can perform a variety of differing tasks, arc welding, spot welding on an automobile line, venting of molds, drilling and routing in the aerospace industry, and a number of other applications. But the key to each one of those in fact, is someone deciding to do that task, and dedicating the resources to make that task happen.

I think this is the challenge that faces us today. The automobile industry, which not only in the United States but worldwide probably accounts for 40 to 50 percent of all robots in actual use today, began with development in General Motors in the Lordstown and Norwood plants back in the late sixties and early seventies. They dedicated a tremendous number of internal resources to understand the technology involved in robotics and in the process, and married these two together for successful applications in both quality and productivity. It took 10 years.

The main point we have to look at today are the programs discussed by Paul Aron and Mr. Arai. Competitors in other countries are providing a tremendous advantage to companies in those countries to apply and use robots. They are thereby expanding not only the robot base, which is one portion of the total situation, but in fact the productivity and quality gains, manufacturing and engineering culture and concepts, the technicians, all of the people it takes to in fact increase productivity and produce quality products. This is probably the challenge that we are facing. We look at the program in Japan with a 52-percent first year tax payout. The lease company has extremely favorable rates. Britain has a very favorable program, I believe it is 50 percent payment for all feasibility studies on robotics, and I believe it is up to 33 percent of all investment in a grant from the Government to install robotics in Britain. These are the areas in which we face severe challenges.

Certainly when we look at the programs in Japan we can look at the development and research programs, these are vital and necessary. But probably more interesting is the shipbuilding industry, where Japan developed, back in the early sixties, probably one of the most aggressive technology programs in shipbuilding the world has seen, in recent years, in any case. They had begun to lose that marketplace to surrounding countries with lower labor rates.

They have just inaugurated a major program to protect jobs, industry, wealth and standard of living in the country by combining shipbuilding companies, robotics companies, university, and the Government in a joint program to put the Japanese shipbuilding industry back at the forefront of the worldwide shipbuilding industry.

I think these are the challenges that we face. I think the so what of this is, in coming back to some of the questions addressed earlier, is that industries or countries that use this technology—and again I have to expand it beyond just robotics, but to the entire area of automation and productivity, flexible manufacturing systems, et cetera—in fact will find themselves in a competitive position in global markets now developing and that have developed. Countries that do not address this as a global issue, do not recognize that the welfare and well-being of the workers of that country, and society and social economic impacts, will find themselves somewhat behind in the competitive situation in the next decade.

Thank you.

[The prepared statement of Mr. Radeke follows:]

Subcommittee On Investigations and Oversight
Committee on Science and Technology
U.S. House of Representatives
June 2, 1982

Comments by Michael Radeke:

The productivity of manufacturing is the single most important determinant of our standard of living, the value of manufacturing and the economic well being of our country.

In the decade of the 1980's, major emphasis must be placed on increasing the productivity of batch-type manufacturing - that sector which produces parts in small-to-medium size lots. Batch-type manufacturing accounts for about three-quarters of all industrial production.

The principal nations with which we compete recognize that robotics are a key element in increasing the productivity of batch-type manufacturing because robots have flexibility to perform a variety of tasks and also adapt to product changeover.

To increase the understanding and use of robotics, competing nations are following two paths simultaneously. On the one hand, they are encouraging technological developments which expand the capabilities of robotics. At the same time, they are working to increase the use of robotics throughout industry.

Technological development programs are aimed at both educational institutions and manufacturers of robots. The principal emphasis is on sensor development, language development and development of computer capability.

Programs to promote the use of robots are somewhat more complex, but are generally of two types. One type reduces the risk to the user in adapting the new technology of robotics to a task in his manufacturing operations. The second type is broader based and involves educational institutions, robot manufacturers and government research institutions. These cooperative programs are aimed at increasing the use of robotics in specific industries which are considered critical to the social and economic health of the country.

To promote the use of robots within an industry, tax incentives are widely used. They usually apply not only to the cost of the robot and ancillary equipment, but also to development costs related to automating the process. Tax incentives usually have some type of low cost financing coupled with them to further encourage installation of robotics. A second method of promoting the use of robotics is by governmental grants - often to industries which do not have the financial resources to install new technology.

The other type of program involves identifying a "critical" industry, and usually one which is finding it difficult to compete with imports from countries having low labor costs. An analysis of the labor intensive portion of the manufacturing process keys the program to seek specific industries for the use of robotics.

These programs bring together the talents of all parties which can provide significant help. The user industry contributes knowledge of the process and task to be done by robotics. Educational institutions provide research in process oriented technology. Robot manufacturers play a key role if a new or different robot configuration is needed. And finally, government administers and monitors the overall program.

I firmly believe that the United States must adopt similar programs to increase the use of robotics throughout American industry. As the Joint Economic Committee of Congress said in its 1979 annual report, "We can and we must produce our way out of our economic problems".

Mr. Gore. Thank you very much. We are honored to have you appear, and company representatives quite well known in this area.

Our next witness, Charles Rosen, is known as one of the leading innovators in this whole area. We welcome you.

Mr. Rosen. I wear two hats. I represent small business, in the sense that I helped start robot businesses in the last 3 years. Prior to that I was one of the people who was developing some of the technologies we have heard about. It is sort of interesting, because I think the two hats are important for this hearing. The next panel, and some of the other folks here from NSF will discuss some of the problems still to be worked on. NSF was one of the few organizations in the Government that foresaw the need for this technology, roughly 10 years ago, when the RANN program began at NSF. That permitted us at SRI International where I worked at for 21 years, to start a program initiating some of this technology and transfering it to industry. We were aided not only by this Government agency but by industry in general. At present there are 25 to 30 industrial firms supporting this work at SRI International.

Mr. Gore. Could you use that microphone, point it toward you a little bit? Thank you.

Mr. Rosen. Unfortunately the amount of such support, both by Government for basic research and industry for applied research was very small. So these centers were few in number. I think that the growth of these centers in the last 5 years is very, very encouraging. Wearing two hats, I can sympathize with the long-term needs of this country in the form of basic research. If we are to maintain the one edge we still have in this country, namely advanced technology that is second to none, and attend to the remaining problems involved in encouraging the widespread use of this technology, one concludes that research has to be supported heavily and increased substantially.

For the near-term, we have heard testimony already covering many important points. There are about 20 million to 25 million hands-on workers in the manufacturing industries. How many of these will be displaced by the year 2000 or 2010? Let us look at what could happen today. Despite the needs for more research and technology, if you look at what these jobs are in the factories, you find that many are material/handling, quality control and inspection jobs, some process control, and of course, a major group called assembly.

But if you examined the movie sequences that were just presented, you would realize that a robot is not put into a factory to replace a man by just buying the robot and shoving it into place and away it would go. It is a system. It has to be integrated with other parts of the production process. In the factory of the future this is going to be even more so.

We talked about Cadman (computer aided design and manufacturing) information systems, inventory control, control of flow, et cetera. In fact we were talking about a future factory that will be a very complicated system, with many subsystems all coordinated by various computers. To introduce robots is just one little piece in that big complex.

The most important problem we found in attempting to get into the robot business (via the sensors route of adding to robots) is that we have to engineer a complete systems to introduce any of our new, more sophisticated automation tools. Trained personnel do not exist in the factories yet. The infrastructure is not there. Companies like ours, many of them starting up now, have limited personnel and limited facilities to do application engineering, and the distributors of machine tools and whatnot who have people that are capable of doing application engineering woefully lack adequate numbers of such personnel. Of that 20 million workers, it is entirely possible that if sufficient system capabilities and application engineering existed today, I would not be surprised if a third to one-half of all the jobs that are hands-on in factories could be handled with the technology either available today, or shortly available within the next 5 years. And that is a pretty big number.

The robot industry cannot presently supply the robot expertise to handle all the jobs that are possible. Of course, I am making the tacit assumption that the money would be available to pay for these capital goods. If you have a small shop and want to put a single robot in and change your operation so that that robot can function properly, you are in for about a hundred grand if you want to use a sophisticated robot and its accessories. Where are they going to raise that kind of money if they have 15 or 20 hands-on workers in that small shop? They just do not have it. The cost of money today is very high, and they are not going to afford such investments for quite some time.

I brought up just a few points here regarding the present situation. The technology existing today could actually revolutionize our factories today. The money does not exist. The trained people do not exist. The vendors who have to support this kind of effort do not exist. All of these needs are yet to be fulfilled. And it will take a heck of a long time for all of this to happen. This is the near-term picture.

As far as the far-term picture, we are talking about the two-thirds or half of the jobs that cannot be done by present-day technology. Here is where we have a big stake in this country—to make sure that we never fall behind in new technology. Therefore, all these research programs that are now being funded in a very, very modest way by the Government and others, especially at Carnegie, MIT, at a half dozen other universities, and at the nonprofits, have to be augmented significantly. The Japanese are not just good implementors. Visit their laboratories. You may be surprised at the degree and quality of innovation. They have implemented our technology and done an excellent job. But they have also started to increase their capabilities for creative developments and creative research in this field, and they intend to be amongst the frontrunners of the research as well as the implementation. And based on past history I have no doubt they are going to do so. There are, therefore, major issues:

Short term, we are faced with great shortages of trained personnel and money, and in the ability to use the technology that exists today. Long term, we are faced with the possibility of being overwhelmed by not only by Japan, but by others. West Germany is no laggard either. All the industrial countries are going to put a great deal of money into the future research.

I have three recommendations that are based on the foregoing discussion:

First, double or triple the amount of money going into research organizations. Such funding should go primarily to universities, because it serves two purposes. First, we will generate the new technology in time. Second, they are the major source of trained people. Where else can you train people that understand this kind of sophisticated technology? Where do you train not only Ph. D.'s, but engineers of all kinds that can get into the factories and actually implement the applications? Universities! Put the money into the universities for research and training.

Second, there is a pending bill to put 1 or 2 percent of the national R&D budget into helping small firms. Why not make sure that that happens. A buck spent in a small firm is worth about $3 or $4 in a big firm as far as getting something into the marketplace in a hurry. I come from Silicon Valley. If any of you have visited, you know exactly what I am saying. There is not a day that passes that there is not a new firm started in the semiconductor or computer industry. They are all growing. Furthermore, all the bucks spent in these small firms are not wasted. The big firms all get their share, because they will buy many of the small firms. That is what has been happening.

Third, maintain and possibly augment the tax incentives passed in the last year. They have been seminally important for initiating new enterprises.

Thank you.

[The prepared statement of Mr. Rosen follows:]

ROBOTICS FOR U.S. INDUSTRY

Prepared for
The Committee on Science and Technology
U.S. House of Representatives

By
Charles A. Rosen
Chief Scientist, Machine Intelligence Corporation

June 2, 1982

Background

The field of robotics is part of a larger field of revolutionary factory automation which will ultimately lead to the implementation of the "Factory-of-the-Future." The new automation, based on the use of computers for every aspect of manufacturing includes CAD/CAM (Computer-aided design/computer-aided manufacturing); computer-controlled machine tools; computer-controlled robots; computer-controlled inspection and quality control systems; factory-wide communication systems; computer programs and data bases for procurement, inventory control, line balancing, process control, flow of work; and man-machine manipulative systems (teleoperators) in which a human is in continuous control of a robot-like machine.

These new systems are characterized by the use of computer programs (software) which once written, can be modified, corrected, and upgraded far more readily than conventional automation hardware. Furthermore, with the development and standardization of general purpose robot hardware, computer programs can be inexpensively duplicated, thus specializing the functions of the hardware for new tasks. This is in contrast with "hard" automation hardware which usually can only be modified or altered at great expense and with considerable delay. This is especially true for batch manufacture (relatively small numbers of assemblies) which comprise over two-thirds the value of manufactured goods in the U.S.

It is universally believed that the new automation will result in greatly increased productivity, increased quality of goods produced, elimination of boring, onerous and dangerous jobs, increase in customization of product and general improvement in the quality of life for workers and the general public.

This presentation will concentrate on the field of robotics and automated inspection, which are representative and important subsystems of the "Factory-of-the-Future".

State-of-the-Art and Limitations of Robotics

The majority of programmable machine tools and industrial robots in use today are first generation machines based on concepts at least 20 years old, making little use of available advanced computer hardware and software. The basic technology and first machines were invented and introduced in the U.S. over 20 years ago and have been exported to other industrialized countries. In particular, Japan has exploited this technology in depth, primarily for use in their own factories, but now beginning to penetrate foreign markets with a variety of industrial robots. The major applications of first generation robots has been generally in material-handling, such as loading other machines, palletizing, etc.

Second generation robots incorporate modern computer processors which permit extension of the applications of industrial robots into many manufacturing processes including spray painting, spot welding, arc-welding, and simple assembly operations. First and second generation robots, so-called "dumb" robots, have little or no sensory inputs, and therefore can only perform a sequence of actions under completely predetermined conditions. For example, a "dumb" robot, programmed to pick up a work-piece from one location and place it in a second predetermined position with a predetermined orientation will fail to do its job if the work-piece is not in a precisely "indexed" or "fixtured" position when the robot acquires it. The robots cannot adapt to changes in position or orientation of the work-piece. In contrast, human workers can "see" the variable positions of work-pieces and "adapt" the motions of their arms, hands, and fingers to properly acquire the work-pieces and properly deliver them to their intended target positions and orientations. By adding sensory inputs to the robots and thereby mimicking human vision, human tactile (touch, force and torque) and/or aural (acoustic) sensing, a third generation of robots, so-called "intelligent" robots, will be able to modify their sequence of actions, adapting to new conditions in real time, able to perform many of the manual operations required for mass-production. These operations include the use of specialized tools mounted in robots' "hands", which can efficiently weld, screw, grind, paint, glue, hammer, drill, etc. Furthermore, these sensory devices have all-important secondary capabilities, that is, automatically inspect work-pieces, assemblies, and work-in-progress, to greatly improve quality and yield of finished products.

At present, only a few percent of all robots now in use in factories are third generation "intelligent robots" and are concentrated in a few factories. General Motors, Texas Instruments, Chesebrough-Ponds and Hitachi (Japan) are reputed to have sizable numbers in use in their own factories. As yet these internally developed systems are not generally available for sale to other companies. Approximately a dozen small U.S. companies are offering vision sensory systems, a few of which have been mated to robots, thus upgrading second generation robot systems into third generation "intelligent" robots. Initial sales of "intelligent" robots are small, primarily to research and advanced development groups, with few direct applications in factories. Sales and use of vision systems for inspection and quality control are more promising and appear to be gaining increasing acceptance in industry. Some factors inhibiting widespread introduction and use of robots are:

- High Cost. Initial costs are high for the equipment and the necessary application engineering required to modify present production methods to accommodate the new technology. In general, after successful design, installation and "debugging" of a prototype system succeeding systems are cost-effective. However, the considerable capital expenditures (at present high interest rates) required to install initial and succeeding systems preclude their early introduction in any but the largest enterprises. Japanese suppliers have partially circumvented this problem by leasing arrangements, at relatively low interest rates, to small firms.

- Lack of Trained Personnel and Experienced "Systems" Distributors. Only a few very large firms have trained personnel able to plan, design, integrate, and maintain the advanced robot systems, especially those requiring combined mechanical, optical, electrical and computer software skills. There are critical shortages in high level professional computer personnel, in management experienced in the applications of the new technology, as well as in "hands-on" personnel skilled in installation, debugging and maintenance. These shortages are similarly experienced by large national distributors of comparable capital goods, such as machine tools. There is a great need for reliable system houses, i.e., distributors capable of either aiding clients to install complete systems or contracting to do the whole job themselves (turn-key system houses). A growing movement is now underway by established and new distributors to build up their capabilities, severely limited by shortages in trained and experienced personnel. At the same time, suppliers of robots, vision systems and anciliary equipment are attempting to fill this gap which inhibits their growth of sales, by supplying their own systems expertise. They, too, however, are limited by shortages in their own trained personnel who are primarily engaged in developing these sophisticated products. Further, small business enterprises who often are at the cutting edge of the new technologies, also have limited financial and material resources to devote to this essential component of marketing their products.

- Limitations of Present Technology. Although a very large number of applications in factories can be now serviced by state-of-the-art hardware and software, the majority of potential applications await the development of higher performance, lower cost robot systems. To a limited degree such components and systems are being developed in universities and research institutes whose prime functions are training and long-range research. Major contributors to advanced nearer-term products are a few very large robot manufacturers and the more numerous small business entrepreneurs who normally have migrated from universities and other research establishments after years of research and development experience in robotics, machine intelligence and computer science.

Required Research

Two classes of research are needed, near-term applied research and development, and long-term basic research.

Historically, most of the major creative concepts in robots, computer technology, machine intelligence and solid state electronics have originated here in the U.S. as a result of basic research. The Japanese have excelled in exploiting the new concepts, applying great skill in design, engineering, and manufacturing high quality products. The Japanese, West Germans, and other advanced technological nations are now providing major government funding to advance their basic research efforts, as well as vigorously pursuing the implementation of workable systems. The U.S. still has a considerable edge in the number of highly-qualified professionals capable of advancing the science of robotics, machine intelligence, etc. Most of them work at universities and research institutes. All too many of them are leaving their preferred vocations as researchers to enter the industrial scene, often driven by the lack of tenured university positions or lack of funds to perform their research. As a minimum strategy, the U.S. must maintain its lead in basic research capabilities, as well as play "catch-up" in the implementation and widespread use of available robot systems. This will require funding for equipment and personnel at many universities and research establishments.

Near-term applied research and development is badly needed in the U.S. to exploit the full capabilities of existing conceptual developments in machine intelligence. In the past five years, hardware (robots and computers) and software components have become available at acceptable prices. The major limitation to full exploitation is the lack of system capability, that is, the capability to develop complete integrated systems composed of available components to do specified tasks. This work can be classified as applied research and development based on good engineering practice. It is costly to develop prototype or pilot systems and few industries have the resources to attempt this. Programs of this sort could well be carried out in the Engineering Departments of universities, research institutes, and the advanced development departments of private firms.

Role of the Federal Government

In the past, the U.S. government has played an indispensable role in sponsoring the research, advanced development and implementation of some of the most important technologies, which today serve as the basis for the remaining industrial leadership the U.S. enjoys. These include computer-controlled machine tools, solid state electronics, computers, aircraft, advanced communications, etc. In robotics and associated machine intelligence, research has been sponsored by the Department of Defense (most early work by DARPA) and by the National Science Foundation. These initially sponsored programs have been relatively small compared with similar programs in Japan and West Germany. The only significant large U.S. program aimed specifically at improving productivity in the aerospace industry is the ICAM program (Integrated Computer-Aided Manufacturing) funded by the U.S. Air Force. In particular, the RANN program (Research Applied to National Needs) and its successors at the National Science Foundation, with annual budgets at most of several millions, have been responsible for the major part of funded research at universities and research institutes in robotics and associated technologies in this country for the past ten years. Small but significant additional support was given to new small businesses by the NSF Small Business Program, which permitted entrepreneurs to obtain seed money for applied research that has led to promising new products.

It is doubtless true that normal profit potential aided by tax-credits for capital equipment and write-offs for R&D expenditures will provide strong positive motivation for the exploitation of the new technologies. However, our foreign competitors are blessed with all of the above incentives, and additionally, by an order-of-magnitude greater government funding at all levels of research, applied research, pilot systems and engineering. If time is of the essence in this competitive race which may affect all our future productivity, we had better not rely solely on normal free-market concepts. I strongly recommend that:

(1) Government funding to universities and research institutes be augmented several-fold to:

  (a) Maintain our long-term basic research supremacy in robotics, machine intelligence, computer science, and solid state electronics.

  (b) Double or triple the available facilities for the training of high level professionals in both science and engineering in these fields.

  (c) Initiate training programs for technicians (software and hardware).

(2) Enact pending legislation that would assign at least 1% to 2% of government R&D budgets to fund small businesses, (especially new entrepreneurs) permitting them to creatively develop new robotics products and systems in the near-term. This small redistribution of available R&D funds should not be made by reduction of the grants to universities, but at the expense of the far larger support of large business enterprises. In the long run large business enterprises will gain from this arrangement, because the majority of successful small businesses are bought up by large businesses to the mutual advantage of both. It is well-known in industry, that small businesses make more effective use of R&D dollars, by far, than large businesses.

(3) Maintain or increase tax incentives to all business for expenditures directly related to increased productivity and/or quality of goods produced.

Summary

1. A second industrial revolution is in progress based on emerging robotics and allied machine intelligence technologies. It will probably take one to two generations to mature, and will directly affect, as a minimum,

the major proportion of the 20 million workers in the manufacturing industries, and to a much smaller degree, some of the 60 to 70 million workers in the service industries.

2. The U.S. now has the fundamental knowledge of the basic concepts underlying the new technologies, and has been slow in capitalizing on the implementation and exploitation of this knowledge. The U.S. is faced with strong international competition not only affecting the market share in the new industry of robotics, but clearly affecting our competitive stance in the production of all our manufactured products.

3. Normal short-term market incentives may be insufficient for U.S. firms to compete successfully with determined foreign competitors who are substantially supported by planned long-term government programs. It is recommended that U.S. government support be given to universities for basic research and training of qualified personnel, to small business for near-term development of sophisticated components and systems, and to tax incentives for capital expenditures aimed at increasing U.S. productivity and quality.

Mr. GORE. Thank you. You were invited here for your knowledge on robots. It is also interesting that you also share my view on the bill pending on the 1-percent set-aside. Let me note for the record that you were a winner in the small business innovation research program at NSF for your work on robotics. In fact, your small business in this area would not be where it is had it not been for the innovative and stimulative program to encourage small business research at NSF on which this larger bill is based. But that is entirely coincidental.

Mr. ROSEN. Could I make a remark, Mr. Chairman, on that? It is easier to get venture capital money for a small business if you have a product in hand, poor as it may be developed, but a product in hand. It is hard to get seed money to make that first prototype product. That is what the NSF small business grant did for our little company. That is why I am so anxious to see more of this happening.

Mr. GORE. I do, too. I want to see a lot more innovators like Charles Rosen in this country.

Let us move now from small business to big business. We are delighted to have Mr. Lothar Rossol, assistant department head of computer science at GM Research Labs, accompanied by Richard Beecher, manager of the robotics, perception and team study with GM's manufacturing development staff.

Mr. Rossol, we are delighted to have you, and please proceed.

Mr. ROSSOL. Thank you, Mr. Chairman, members of the subcommittee. We are pleased to have this opportunity to present our views on the role of American industry in the development of robotics.

As you have recognized, there is a serious need to improve the economic well-being of our Nation so that the United States may successfuly compete in the world marketplace. We are convinced also that robotics will play a major role in transforming GM and other industrial plant operations in the years to come.

You may be interested in knowing that, in 1961, GM pioneered the automotive use of this technology when a robot was placed in operation unloading a die-casting machine. By 1980, we were using about 300 robots, primarily in one application—spot welding. We now have approximately 1,600 robots on hand or on order. We expect this number to continue to increase.

At the GM Technical Center, an extensive robot laboratory has been established, and it has had as many as 35 different experimental robots in operation at one time for evaluation or demonstration. In the past year, over 6,000 GM engineers and managers from around the world have visited the laboratory. We would be pleased if your committee or other Government officials would visit our technical center to see this and other exhibits of advanced technology.

In addition, General Motors has led the industry in the development of visual sensor-based robot systems. These include:

Consight: A system which looks for randomly positioned parts on a moving conveyor belt and directs a robot to pick them up.

Sight-I: The first industrial application of computer vision in the United States. It is a vision system which inspects integrated circuit chips and automatically positions electrical probes to test the chips.

Keysight: A vision system that inspects engine heads for missing valve keys.

In our comments, we would like to touch briefly on the limitations of current robots, research areas that should be emphasized, and the role, if any, to be played by the Federal Government.

The robots commercially available today are being successfully used in a variety of applications. They can perform relatively complex tasks—such as component assembly—and simpler ones, like material handling.

But there are many things today's robot is incapable of doing or is incapable of doing on a cost-effective basis.

In most installations, the robot is programed to perform a certain repetitive routine. But the robot cannot become aware of, and thus cannot adapt to, changes in the workplace. As a result, we have failures which can result in damage to the robot, to the workplace, or to other tooling or fixtures.

Another deficiency is the robot's relatively slow speed. Many of our production operations require robots to complete a task in 3 seconds or less—but the robots of today are simply not that fast.

We have identified three problem areas requiring more underlying basic research to support the use of robotics in new applications. These problem areas are in sensor systems, robot control systems, and robot programing technology—which are all related. Let us look at each of them in somewhat more detail, starting with sensor systems.

In the future, many robots will be controlled by sensors. These sensors will provide information to the robot so that parts, surrounding equipment, and the robot itself need not be precisely located or dimensioned; instead, the robot will adapt to changes in its environment. Additionally, sensor systems would provide general inspection capability.

The relevant sensors will be range, force—or touch—and, most importantly, vision. Although much can already be done with machine vision, we cannot yet claim that computers or robots can actually "see" in the usual meaning of the word.

In fact, most industrial vision tasks are not solvable today. This is because we do not understand vision—biological or artificial. Each vision system we have developed to date can handle only one narrow class of problems. A better understanding of the basic processes of vision must therefore be achieved.

Additional understanding is also needed with respect to the other robot senses—range and force. Although some experimental three-dimensional vision machines can measure range, we do not yet have a good understanding of general range or force sensing systems.

The second major area where we lack basic knowledge is in robot control systems. Such systems now normally consist of several computers, some special-purpose electronics, and the software for the computers. Two issues are important here—robot speed and adaptive control.

Adaptive control involves the integration of information from vision, range, and force sensors into the control software and electronics of the robot in order to adapt the motion of the robot arm to changes in its environment. Such control theory is an open research area today.

The third problem area is that of robot programing. Currently, a robot is taught by manually guiding it through predefined motions. The positional information must be stored in the robot's memory before it is able to repeat the motions.

Moreover, programing would have to change if a sensor-controlled robot were involved. There could be no predefined motions for use in programing, because the path of the robot arm would vary according to its sensory inputs.

Generally, at programing time the robot itself would not be available, the part not yet built, and the production line not yet set up. All the necessary information would likely exist, however, in computer-aided design data bases. The idea would be to program robots using such data. But this requires basic research in support of the programing issues because we do not even have concepts for off-line programing of conventional robots—let alone sensor-controlled robots.

In our opinion, the three topics mentioned here constitute the most important areas for which new underlying scientific knowledge is required.

We believe basic research is the appropriate area for Government involvement, and that the underlying work in support of the three topics we have discussed is most important for the robot community.

Admittedly, the definition of basic research is not precise, but it can be roughly described as an effort to expand scientific knowledge and understanding rather than the application of such knowledge to the development of specific products. Government research that goes beyond the discovery of new knowledge unavoidably places the Government on a parallel path with industry. Such unnecessary duplication is an inflationary waste of taxpayer dollars. In our view, the Federal Government should not be a competitor of industry, but rather a supportive ally. Long-term policies and programs must be designed to foster increased productivity.

We have found the industrial affiliate programs—as exemplified by those at SRI International and the University of Rhode Island—to be useful. Such programs allow a synergistic relationship to be established between the research institution and private industry. This does not mean, however, that affiliate programs should be the sole mechanism for doing basic robotics research. Universities should also perform independent Government-sponsored robotics research.

We hope the perspective we have offered on industrial robotics will prove useful to you.

Thank you.

[The prepared statement of Mr. Rossol follows:]

STATEMENT OF GENERAL MOTORS CORP. ON INDUSTRIAL ROBOTICS USE AND FUTURE RESEARCH NEEDS

Good morning, Mr. Chairman and Members of the Subcommittee.

My name is Lothar Rossol. I am Assistant Head of the Computer Science Department with General Motors Research Laboratories. With me today is Richard Beecher, manager of Robotics, Perception and Team Study with General Motors Engineering Staff.

We are pleased to have this opportunity to present our views on the role of American industry in the development of robotics.

As you have recognized, there is a serious need to improve the economic well-being of our nation so that the United States may successfully compete in the world marketplace. We are also convinced also that robotics will play a major role in transforming GM and other industrial plant operations in the years to come.

You may be interested in knowing that, in 1961, GM pioneered the automotive use of this technology when a robot was placed in operation unloading a die casting machine. By 1980, we were using about 300 robots, primarily in one application -- spot welding. We now have approximately 1,600 robots on hand or on order. We expect this number to continue to increase.

At the GM Technical Center, an extensive robot laboratory has been established and it has had as many as 35 different experimental robots in operation at one time for evaluation or demonstration. In the past year, over 6,000 GM engineers and managers from around the world have visited the laboratory. We would be pleased if your committee or other government officials would visit our Technical Center to see this and other exhibits of advanced technology.

In addition, General Motors has led the industry in the development of visual sensor-based robot systems. These include:

- CONSIGHT - a system which looks for randomly positioned parts on a moving conveyor belt and directs a robot to pick them up.
- SIGHT-I - the first industrial application of computer vision in the United States. It is a vision system which inspects integrated circuit chips and automatically positions electrical probes to test the chips.
- KEYSIGHT -- a vision system that inspects engine heads for missing valve keys. It is the first system of this type installed in any U.S. plant.

In our comments, we'd like to touch briefly on the limitations of current robots, research areas that should be emphasized and the role, if any, to be played by the federal government.

Limitations of Today's Robots

The robots commercially available today are being successfully used in a variety of applications. They can perform relatively complex tasks -- such as component assembly -- and simpler ones, like material handling.

But there are many things today's robot is incapable of doing or is incapable of doing on a cost-effective basis.

In most installations, the robot is programmed to perform a certain repetitive routine. But the robot cannot become aware of, and thus cannot adapt to, changes in the workplace. As a result, we have failures which can result in damage to the robot, to the workpiece or to other tooling or fixtures.

Another deficiency is the robot's relatively slow speed. Many of our production operations require robots to complete a task in three seconds or less -- but the robots of today are simply not that fast.

Problem Areas Needing Underlying Basic Research

We have identified three problem areas requiring more underlying basic research to support the use of robotics in new applications. These problem areas are in sensor systems, robot control systems and robot programming technology -- which are all related. Let us look at each of them in somewhat more detail, starting with sensor systems.

In the future, many robots will be controlled by sensors. These sensors will provide information to the robot so that parts, surrounding equipment and the robot itself need not be precisely located or dimensioned; instead, the robot will adapt to changes in its environment. Additionally, sensor systems would provide general inspection capability.

The relevant sensors will be range, force (or touch) and, most importantly, vision. Although much can already be done with machine vision, we cannot yet claim that computers or robots can actually "see" in the usual meaning of the word.

In fact, most industrial vision tasks are not solvable today. This is because we do not understand vision -- biological or artificial. Each vision system we have developed to date can handle only one narrow class of problems. A better understanding of the basic processes of vision must therefore be achieved.

Additional understanding is also needed with respect to the other robot senses -- range and force. Although some experimental 3-dimensional vision machines can measure range, we do not yet have a good understanding of general range or force sensing systems.

The second major area where we lack basic knowledge is in robot control systems. Such systems now normally consist of several computers, some special purpose electronics and the software for the computers. Two issues are important here -- robot speed and adaptive control.

Adaptive control involves the integration of information from vision, range and force sensors into the control software and electronics of the robot in order to adapt the motion of the robot arm to changes in its environment. Such control theory is an open research area today.

The third problem area is that of robot programming. Currently, a robot is taught by manually guiding it through pre-defined motions. The positional information must be stored in the robot's memory before it is able to repeat the motions.

Moreover, programming would have to change if a sensor-controlled robot were involved. There could be no predefined motions for use in programming because the path of the robot arm would vary according to its sensory inputs.

Generally, at programming time the robot itself would not be available, the part not yet built and the production line not yet set up. All the necessary information would likely exist, however, in computer-aided design data bases. The idea would be to program robots using such data. But this requires basic research in support of the programming issues because we do not even have concepts for off-line programming of conventional robots -- let alone sensor-controlled robots.

In our opinion, the three topics mentioned here constitute the most important areas for which new underlying scientific knowledge is required.

Role of the Federal Government

We believe basic research is the appropriate area for government involvement and that the underlying work in support of the three topics we have discussed is most important for the robot community.

Admittedly, the definition of basic research is not precise, but it can be roughly described as an effort to expand scientific knowledge and understanding rather than the application of such knowledge to the development of specific products. Government research that goes beyond the discovery of new knowledge unavoidably places the government on a parallel path with industry. Such unnecessary duplication is an inflationary waste of taxpayer dollars. In our view, the federal government should not be a competitor of industry, but rather a supportive ally. Long term policies and programs must be designed to foster increased productivity.

We have found the industrial affiliate programs -- as exemplified by those at SRI International and the University of Rhode Island -- to be useful. Such programs allow a synergistic relationship to be established between the research institution and private industry. This does not mean, however, that affiliate programs should be the sole mechanism for doing basic robotics research. Universities should also perform independent government-sponsored robotics research.

We hope the perspective we have offered on industrial robotics will prove useful to you.

Thank you.

Mr. GORE. Thank you very much.

Chairman Scheuer.

Mr. SCHEUER. Is this the time to ask questions?

Mr. GORE. Mr. Beecher, I take it, does not have a statement.

Mr. BEECHER. No, sir.

Mr. SCHEUER. Thank you, Mr. Chairman.

Mr. GORE. You are recognized for 5 minutes.

Mr. SCHEUER. It has been an extraordinarily interesting panel. All of you have given us much to chew on. There is very little you have said that I will take objection to, and very much that you have said that I think helps move our thinking along.

I would like to ask a couple of questions, addressing ourselves to the Japanese experience. First I would like to ask any of you what the proper role of the Federal Government is compared to MITI, which actually provides research and development funds, selects the industries in which they are going to make a quantum jump forward, provides research and development grants, takes two or three major companies, creates the consortia, funds the consortia, gives them the product or the industry they want to go. That has been their traditional pattern, of not only funding the research, but deciding the industry, almost defining the product, selecting the corporations. And then providing the research design and the funding. That is in the Japanese tradition.

It is not quite in our tradition. Let us pick and cull. What are the elements of the Japanese success that you think are applicable here, and what permanent mutations and combinations of change do we have to make to define what is a proper Federal Government role for this country? That is my first question.

My second question, I want to ask the two questions in my 5 minutes, at least, the second question is based on my feeling that industry is basically on the right track, that they are moving, the market forces are working. There is an absolute inevitability about our moving into this whole field of robotics and allied sophisticated applications of the computer.

I see the problem of labor unions, and I see the problem of the threat that will be perceived by individual workers to be a much greater problem in this country than it has been in Japan for some of the reasons we have already discussed. How do you all perceive this, and how do we meet the human needs of the workers who are not right on target and who are not ready to hit the deck running, and to participate in this whole computer revolution, who do not have the skills right now to be retrained? How do we include them in, as Samuel Goldwyn would have said? And what is the role that industry can play?

It is common knowledge that our education system, our elementary and secondary education system to some degree has turned off kids. Without trying to assay right and wrong and guilt, pointing the finger, the education system for a lot of our young people, a lot of our young minority people, has not involved them, it has not challenged them, it has turned them off. There are some people who say well, education at the traditional school site has failed. Maybe we ought to try education on the job site. Maybe we ought to design a work-study program that includes a lot of education, where they will be paid or released time, they will be compensated. That this turns the kids on.

It seems as you are doing computer applications, development and applications of more sophisticated robotics just as Mr. Radeke and Mr. Rosen have talked about, not only designing the computers but applying the computers to the roles that have to be accomplished, a very practical intervention, it seems to me we have to do some very practical thinking about how we defuse this potentially threatening situation, threatening the future application and acceptance of robotics and other computer applications.

How do we create an American labor movement, particularly among our young people, that will welcome it as the Japanese have, instead of feeling it as a direct threat to their futures, their psyches, their persona? How do we include them in and give them the literacy and numeracy tools so that they will accept it and welcome it? Does the corporation have a role in training and educating and providing the requisite skills to the workers during the 2- or 3-year period that you may have when you have once decided to eliminate a particular production line, and wipe out 300 or 400 jobs, and put in a computer so you will have 5 guys on 2 shifts and then the night watchman and maybe somebody watching a whole wall of computer panels? What role can industry play in that human retooling challenge?

Those are the two questions that I have: What is the proper role of the Federal Government in all of this? And what is a really creative and innovative role for industry and business itself to play in the human engineering or reengineering, as well as in the design of the computer hardware?

Have my 5 minutes expired, Mr. Chairman?

Mr. **Gore**. We will extend it for the answers.

Mr. **Radeke**. I would like to address the second question. The first one is a much more complicated one, as you all are aware. I think as we look at that, I guess you would call that worker reluctance. That is a good term. To be very honest, we have not seen it at all in the industry. First we have the size of the industry. We are looking at 5,000 robots installed. They have not taken over the world, regardless of what Star Wars may want us to think. In general the worker reluctance has been zero. The jobs that they are now doing are much more rewarding than the ones they have done before. In fact, very few industries that I am aware of that have installed robots, in fact, have displaced people.

A worker now is controlling the cell that produces goods, as opposed to physically doing the work himself. There is an article that was done by a newspaper in Indiana on an installation, Cummins Diesel, which I have framed in my office, because the worker was doing a job, a similar one to the film here, moving parts, putting it in a machine, et cetera. He was then replaced with a robot. He now ran two machines and a robot. His comment to the press was when that thing goes down he is on the maintenance force 100 percent, because otherwise he has to do all that work physically himself. And it is so much more fun and enjoyable to run that cell and control that equipment, and be in charge of the production as opposed to being the production.

Mr. **Scheuer**. Let me ask, what percentage of workers whose jobs will be replaced by computers are capable of managing and controlling that computer with how much additional skills upgrade?

Mr. **Radeke**. I guess I have to start from a basic point. I heard a comment earlier that it is going to be very difficult to upgrade the U.S. workers in skills to handle this technology coming in. I do not personally agree with that. I happen to disagree with it. I have found very few workers that I have dealt with at any level within our company or the companies we deal with that are not eager to use the skills that God gave them. I think many times they have not had the opportunity to do that. We certainly have put them in jobs that deny them the opportunity to do that.

I think that in every case, and we have a great deal of training in our company for our customers and conjunctive with our customers like General Motors, the general reaction to that training is 95 percent favorable. Obviously there are some areas where the viewpoint is, "No, I do not want to be replaced, I do not want to do this job, I want to do that job, the one I have done all my life." Certainly that inertia exists, and there is no denying it. But in general when we go through the training programs, there is not a desire to thwart the task, but in fact a desire to participate and get retrained.

We have a program where we have donated robots to about 12–15 different universities and vocational colleges, along with curriculum help, again to solve the problem Mr. Rosen addressed earlier "of where are we going to get the manufacturing engineers, the technicians and self-supervisors and other people". I am very pleased these programs are being set up, vocational programs, particularly in Michigan, South Carolina, and other user States. They are taking these people who we might say are difficult to train and training them for this technology. They are finding great acceptance as far as finding jobs in a very tough marketplace. So I think there are a variety of roles there to be played on that issue.

I think certainly the industries themselves run a large number of retraining programs within their own companies. Certainly our company is involved in a variety of technologies, not just robots but machine tools, plastics equipment, and so on. We have the capability of retraining across any of those other disciplines. If, in fact, the displacement on putting a bolt onto an automobile gets done now by a robot, you certainly do not want to train that person to put a piece of trim on the automobile. You want to train him to do something totally different. Run a machine tool. Be a cell operator. Get involved in the other areas of the manufacture.

So there is a whole task I think we face in this training area in the next decade as we go through the social transformation. And it will occur. The social transformation, if we are going to maintain ourselves competitively in a world marketplace, will occur. We must be prepared both as manufacturers of equipment, as users of equipment, as educational individuals, and as Government to make certain that looking downstream, we recognize that "threat and opportunity" and capitalize on the opportunity part.

Mr. **Scheuer**. Mr. Rosen.

Mr. **Rosen**. I would like to address both your questions. I already stated that the long-range research that goes on that keeps us competitive is not going to be done anywhere but in these universities and nonprofits that are looking toward 10-year improvements in basic science. I do not think that industry in general will put enough effort into it by themselves, because they have enough to do just to implement what there is. You have heard some of the problems my colleagues here have raised. The Government must, I believe, intercede in the basic research field. It must support that basic research in whatever way it can, and indirectly support the training of high-level professionals.

I just came from Carnegie yesterday. I saw an array of available computer facilities larger than I have seen anywhere except perhaps in one of our agencies that cannot be named. An enormous facility. They have 150 or so people working in robotics and allied automation funded by combined industrial-Government research grants. This is a very advanced artificial intelligence community, but one fact stood out. There are only 20 or 25 graduate students. This is one of the major university programs in this country. And only 20 or 25 graduate students going through that kind of training! It is ridiculous for a country this size. There are not more than a half dozen universities that are capable of doing this kind of work. So I want to see the Government intercede, at least in the educational field. By granting research grants and increasing grants sufficiently you will get both of these things to happen.

Mr. GORE. How many of the 20 or 25 were American?

Mr. ROSEN. You know, I do not know, but looking around, not all. Not all. That is right.

Mr. GORE. Go ahead.

Mr. ROSEN. The second thing of course, concerns these entrepreneurs, of which I am one. We need seed money. And we do have trouble getting seed money. That is why the small business bill is very important. I think that the near-term implementation of the technologies we have will be accelerated enormously if people who want to be entrepreneurs, people who want to start their businesses, can do so with a little help, not a lot. That is two. That is about all I would say the Government should do. I do not agree that Government should go in to help specific industries and pour enormous amounts of money into those industries. I think industry should take care of itself.

The second question perhaps is more important than the first one. I give talks to high school students about robots. The students are generally excited. Most of the kids who come are the ones who are playing around with these little personal computers related computer perpherals, that are in the high schools now. They are beginning to be widely available. Kids come in and play around. First they start with those damn computer games. Pretty soon they say, "Gee, maybe I can make some games." Soon afterwards they say, "Now what else can we do?" They have little equipment that is relevant to what we are discussing today to pursue that role. (Remember the radio amateurs in the previous generation.) If somehow these kids could be given some equipment and some teachers, which, of course, are woefully lacking, you would turn on a whole generation of kids who are inclined that way.

There is a technical fact that you must be aware of. My company and many others are trying to make equipment that is easy to set up and train and operate. In fact, the movie showed that with that little box, that you could train that robot to do its various things. I have never seen anybody in our laboratory or any visitor that could not learn how to operate that box in a half an hour. Once taught, he would begin to fool around making the robot do its tricks. The present robots have been designed so that a relatively untrained person can become a trained person quickly. Most people know how to work the box in a very short time, and then begin to learn how to make shortcuts.

For all the other equipments we are talking about, the sensors that are going to be attached to the robot, the more intelligent robot, the robot manufacturers and people supplying those equipments will have to make them extremely simple to use in the factory. The sophistication should be buried in the software programs that make the robots simple to be used in the factory. It is one of the great challenges to make a sophisticated robot that takes a kid to train. I am not worried about those people that have to be retrained, with the exception of just a few who are scared stiff. They do not want to do it. Or they are afraid they will never be able to do it. But the majority of them can.

Whether we will have enough jobs for these people is a separate issue. Whether you can train them I have no doubts. I think it is going to be the robot manufacturers and industrial people who will have to be forced to train these people, because they have nowhere else to go. As for the trade schools, there are just too few of them, there are too few teachers. You are going to have to teach the people right in the factories.

Mr. **Gore**. Mr. Rossol.

Mr. **Rossol**. There are two of us from General Motors and we will each take a question. Being first, I will take my choice.

On the idea of reluctance to retrain, there is a new "disease" which is afflicting some U.S. teenagers and that is their addiction to computers. They breathe, live, think computers all their waking hours. A sample is my teenage son. I bought him a computer, gave him the manuals and now there is only one thing in his universe—computers.

This gives you an indication that, at least in the long-term, the interest is there. I don't believe there is reluctance.

Mr. **Gore**. Mr. Beecher.

Mr. **Beecher**. Just a brief statement with apologies to the academic side of the hearing. There are many, many jobs within the field of robotics, not all requiring a university education.

As Dr. Rosen said, the move is to make the industrial robot easier to program. The level of skills required to program them is therefore considerably lower than it has been in the past.

I have the robot laboratory to which Mr. Rossol referred earlier. One of the most frequent tasks in that laboratory is to give tours to visiting teenagers and grade school kids from the immediate area, Detroit, Warren and the environs.

These are very, very excited by robots and where possible, we give them hands-on experience with them.

With regard to what Mr. Scheuer referred to as the basic literary skills, that certainly is essential. They can't do much without it.

Mr. **Scheuer**. Literacy skills.

Mr. BEECHER. I am sorry, I misspoke. Without them, we cannot do much.

Mr. GORE. Mr. Volkmer.

Mr. VOLKMER. I would like to direct my question more to some of the practical aspects of some of the previous testimony by the previous panel.

Mr. Radeke, do you find any problems with management in implementing robotics?

Mr. RADEKE. Yes, Mr. Volkmer, the answer is yes and no, how's that? Certainly when we deal with presidents and vice presidents of companies. Absolutely not.

They recognize the survival of their company as a viable economic unit is dependent upon them being competitive in domestic and foreign markets.

Therefore, from their view, the long-term investment in technology and automation is an important factor. I have to be honest and say that the place we normally have a reticence to install and use robots are at middle and lower management.

It represents to some degree a total change in what they manage. We have trained in this country a large number of managers that are very, very skilled in management of workers, of people.

We have not trained a large number of managers skilled in the management of equipment and the resources it represents.

So to that degree, it represents some sort of threat.

Mr. VOLKMER. Now, along that line, just to give me basic information, approximately—let me ask you first, about how many robots would your firm manufacture annually now?

Mr. RADEKE. We don't publish that information.

Mr. VOLKMER. All right, okay.

Mr. GORE. A bunch of them?

Mr. RADEKE. More than two.

Mr. VOLKMER. We realize that, but let me ask you this; do you feel that the field of robotics can be greatly expanded in this country?

Mr. RADEKE. Oh, absolutely.

Mr. VOLKMER. What is the reason that it is not at the present time?

Mr. RADEKE. I think there are several. One is the area I addressed, the area of applications.

Let me give you an example which may be helpful. I talked with my counterpart in a Japanese company several weeks ago and they manufacture and market in Japan and market those systems here in the United States.

In the course of our discussion, he said he has not been doing very well in the United States and he says: "I really don't understand why."

I thought about the question for a moment and I said: "Well, who do you sell to in Japan?" and he said: "Well, I sell to welding engineers."

Well, right there we have a basic problem.

The U.S. graduates in the range of 200 welding engineers, manufacturing engineers skilled in the welding arts, in a year. Japan is between 2,000 and 3,000, Western Europe is probably 4,000, if I remember, the Soviet Union is about 8,000.

So what he is trying to do is sell a high-technology project in an area where it is a very much "Missouri-kind" of atmosphere, show me it can do the job and I will buy it.

So if we look at our development expenditures in our company, we are looking at 50 percent of development of product, new product, new capabilities; and 50 percent of applications development, showing people how to use the robot, developing these applications for customers.

If there is one area I am concerned with, it is the one I directed my immediate discussion about, is getting a position where the risk to the user is reduced in introducing this new technology at whatever level the technology represents.

Mr. VOLKMER. In other words, the risk factor creates much of the resistance?

Mr. RADEKE. Yes.

Mr. VOLKMER. Mr. Rossol, on GM, do you manufacture your robots for your own use?

Mr. ROSSOL. Yes, sir, we do.

Mr. VOLKMER. You do not or do you manufacture for others?

Mr. ROSSOL. We do not manufacture for others.

Mr. VOLKMER. In other words, it is in-house.

Mr. ROSSOL. Yes.

Mr. VOLKMER. Do you ever plan or do you know if there is any plan for GM to manufacture for sale to others?

Mr. ROSSOL. I am not aware of any plan to manufacture robots for sale to others. There is the joint-venture company, of which GM is a part, that will, in fact, manufacture and sell to others.

Mr. VOLKMER. Right now, your program, then, is related to the automotive field explicitly and that is it?

Mr. ROSSOL. Yes.

Mr. VOLKMER. Mr. Rosen, can you tell me as far as what work is being done, if not you, anybody else; as far as I see as part of the problem as familiarizing other industries to the use of robots?

Mr. ROSEN. About 90 percent of American marketing effort is sending people out to factories and showing them, back to this Missouri—with hand-carried equipment how the stuff works, what it can do, walking through their plants and saying, here, here, here, here, here are places where it can be applied.

Then the second and much harder job occurs, they see they can use the equipment but it requires a whole system application group to work it up.

That is costly. If it is a small company like ours, we can just devote a small amount of our resources to that costly working up.

We then have to influence that company to pay the piper, like General Motors did at Lordstown for spot-welding.

That is, to make the first installation and make it work because there may be 10's, 20's, 30's, or hundreds of similar applications in that factory.

But that first breakthrough of getting that first system running and somebody paying for it, that is what it is all about.

Mr. VOLKMER. Is the cost factor—and I will conclude, Mr. Chairman—is the cost factor with smaller companies to bring them in, is that a resistant factor, also?

Mr. **Rosen**. Oh, when—we rarely get a very small company, say a company that has 50 or 100 employees that will even begin to consider paying for that first installation.

They are going to follow a great deal what happens in the larger companies, whether it is spot-welding or material handling, they want to see it work and then get the money.

Mr. **Volkmer**. Thank you, Mr. Chairman.

Mr. **Gore**. Thank you.

Let me ask you a few quick questions. Mr. Radeke, your film used a figure of $6 an hour for the P-3 robot. Does that mean $6 an hour for 24 hours a day? How do you figure that?

Mr. **Radeke**. That is based on two shifts normally. Say that figure today is—that film is about 2 years old, it is $8 to $10 now.

Mr. **Gore**. $8 to $9 an hour based on what amortization period?

Mr. **Radeke**. Looking at a 5-year amortization.

Mr. **Gore**. At what interest rates?

Mr. **Radeke**. I think that was done, then, at 17 percent.

Mr. **Gore**. So if interest rates ever come down, you would expect to see an acceleration of the placement of robots?

Mr. **Radeke**. Yes, if we look at any long-term investment, if the interest rates come down, we will see a major retooling.

Mr. **Gore**. You talked about social transformation, can you give me some way to assess the magnitude of the transformation you are talking about?

Mr. **Radeke**. I think we can go back to Paul Aron's type of thinking, we are talking about 15,000 robots, six people, et cetera, so you are talking about 100,000 people.

When we look at that, we have to recognize we are talking across a decade, so the magnitude of the problem today is not significant.

If we look off 10 years from now and take no action today, we will have a significant problem. The key is to start programs today in industries like ourselves, General Motors, so on, universities, governmental areas, to start these things in the right direction, I think this is the area.

I don't know if you noticed this, but in the press recently, there have been comments concerning the unions getting together with MITI and so on to start discussing long-range social implications. It is not that the workers are resistant to the robots coming into their industries, because they see the benefits, but they want to formulate a long-range national policy on how social implications will be handled 5, 10, 20 years from now when we will have the problem, if we don't address it today.

Mr. **Gore**. Is it accurate to say that when one projects the social impact, one is dealing with an exponential curve?

Mr. **Radeke**. I certainly hope so.

Mr. **Gore**. Well, if you——

Mr. **Radeke**. If you look at the needs to be able to be competitive in the world markets, yes, we would hope to see a substantial increase in the types of automation we are talking about, plus, of course, that is cumulative.

If you ship the same amount of equipment, the sum total installed goes up exponentially.

Mr. **Gore**. When will industrial robots be able to adjust to errors in parts positioning in assembly operations?

Mr. **Radeke**. I think GM has one operating today.

Mr. **Gore**. When will we have robots cooperating the same task?

Mr. **Radeke**. We already do that.

Mr. **Gore**. So much for the futures question.

Mr. **Radeke**. The point to make is with the capability of doing those things, and there are installations, yes, of doing that.

But how widespread is that technology, I would say it is very, very narrow.

Mr. **Gore**. You emphasized research into robot vision and interface with other systems, Mr. Rosen. Can robots see at the present time?

Mr. **Rosen**. Well, the product we have is a vision system, very similar to the ones that Mr. Rossol has described in use now at GM. For many millions of jobs with a little rearrangement of the manufacturing process, these systems can be put to use now, but not with the kind of cost-effectiveness that will be available later when the newer systems—which are on the drawing boards right now—will reach the market.

Mr. **Gore**. Now, if you take one of the systems that are currently available, what would be the average initial investment cost per company desiring to purchase and install a robot?

Mr. **Rosen**. Well, the robots of the complexity we have seen start out somewhere around $45,000, $50,000 apiece, and go up to $100,000, $125,000, depending on the application.

If you want a so-called intelligent robot integrated with other equipment, you may add another $25,000 to $30,000 to it, not counting other rearrangements of the manufacturing process.

Therefore you are in for an expenditure of about a $100,000 for a sophisticated task.

Mr. **Gore**. Both you, Mr. Rosen, and Mr. Radeke, in order to sell a robot to some manufacturing company, say, you have to first demonstrate to that company manager how the robot will help him out.

Mr. **Rosen**. Yes.

Mr. **Gore**. Do you find that the manufacturers, you as manufacturers have to perform this systems engineering and analytical function for your customers?

Mr. **Rosen**. Very few of them can. They don't have the personnel. It is only a few big fellows—GM, for instance—that have the personnel and the research and advanced development laboratories that can perform that function.

Most of the other manufacturers are just beginning to hire on their first people that know anything about it and they are trying to get robot manufacturers and other peripheral manufacturers to supply that expertise.

They don't know how to do it.

Mr. **Gore**. If a young person wanted to acquire that skill that will be in such enormous demand, where would he or she go to school for training?

Mr. **Rosen**. There are only a few universities, very few that do undergraduate training at all.

It is just now that the engineering departments, rather than the computer science departments, are starting new teaching programs for this industrial engineering type of skill.

Mr. **Gore**. Could you name them, Carnegie-Mellon, who else?

Mr. **Rosen**. MIT, Rhode Island, Stanford, University of Michigan, University of Illinois, and a few others. These are all just beginning.

Mr. **Gore**. Mr. Rossol, how many robots does GM use now today?

Mr. **Rossol**. GM has 1,600 robots, either installed or on order.

Mr. **Gore**. How many of them are being used for spot-welding?

Mr. **Rossol**. 400 to 500 of them.

Mr. **Gore**. And the others?

Mr. **Rossol**. Machine loading, unloading, material handling, painting.

Mr. **Gore**. Are you doing research in the flexible manufacturing system area which Japan emphasizes?

Mr. **Rossol**. We are doing research in computer-based manufacturing in general. We don't call it quite by the same name, but the answer is "Yes."

Mr. **Gore**. Now, you mentioned this joint venture. That is with the Japanese company, is it not?

Mr. **Rossol**. Yes.

Mr. **Gore**. Fujitsu FANUC.

Mr. **Rossol**. Yes.

Mr. **Gore**. It is a joint venture to design, manufacture, and sell robots. Do you think that arrangements of this kind are going to be commonplace?

Mr. **Rossol**. It is a departure from the way GM has historically done things, so perhaps it could be considered an experiment. If it works out well, then I think that in the future we will see more of this kind of thing.

Mr. **Rosen**. Can I make a remark on that, Mr. Chairman?

Mr. **Gore**. Yes, sir.

Mr. **Rosen**. My little company has just entered into a joint venture with a company in Japan for robots, so that we can put our equipment on their robots and sell an intelligent robot.

Maybe we are a small company that is one of the first to do so, however, IBM; GE, GM, Westinghouse, and others. Westinghouse, all of them have either engaged in joint ventures or cross-licensing as Unimate Corp. has for well over 20 years, and it is my impression that this will be the most common thing that happens to U.S. industry in this field in the next 10 years.

Mr. **Gore**. Why?

Mr. **Rosen**. The Japanese have developed and implemented many applications and good high-quality robots and technology in robots.

We have very great computer and software capabilities in this country and the marriage is very good for both.

Mr. **Gore**. Well, it could be better if we could get partners in the United States.

Mr. **Rosen**. It is very hard to do so.

Mr. **Gore**. Very hard to do so.

Mr. **Rosen**. Yes, sir.

Mr. **Gore**. Well, OK.

Have there been any—this is my final question before turning to our discussants.

Have there been any significant studies of safety and health effects of robots? That may be premature.

Mr. ROSEN. Just safety. The Bureau of Standards is one of the few R&D establishments that is looking into safety aspects and developing devices so that the robot won't kill itself, people, or other equipment.

I think your company—Cincinnati-Milacron—has been interested in that as long as I have known your company.

Mr. RADEKE. Yes.

Mr. ROSEN. There are few research programs associated with that aspect.

As far as health is concerned, I don't know of any effects that would be unhealthy for workers.

Most of the newer robots are going to be electrical and even hydraulic machines; I don't think they present any health problems.

Mr. GORE. Probably very positive aspects.

Mr. ROSEN. Very much so.

Mr. GORE. Did you want to comment, Mr. Radeke?

Mr. RADEKE. Yes; just that the area of safety is addressed by the professional society, the Robotics International of the robot industry.

Mr. GORE. Is there a greater danger as we go to software-controlled robots as contrasted with the lead-through and walk-through approaches?

Mr. RADEKE. Our robot is computer-controlled and always has been, so I think the question is, if I look at off-line programing versus local programing—is that what you are asking?

I think there is no danger from the programing viewpoint, but if we look at automatically starting and programing those robots remotely; yes, that could pose a problem.

Mr. GORE. Who is looking at that?

Mr. RADEKE. Several people are looking at that and seeing how to solve that problem. We are addressing that with our customers. It is a difficult task.

Mr. GORE. Mr. Rosen.

Mr. ROSEN. I don't think hardly enough is being done in that field.

Mr. GORE. Well, very good.

Mr. VOLKMER. Mr. Chairman, just briefly.

Mr. GORE. Mr. Volkmer.

Mr. VOLKMER. I would like to ask, maybe one can answer and the rest can agree or not, how many hours do we operate a robot now without down time?

Mr. ROSEN. Maybe you have a figure?

Mr. VOLKMER. Number of hours.

Mr. RADEKE. I will let Dick answer that, he has done extensive testing.

Mr. VOLKMER. An average.

Mr. RADEKE. Let me say, again, it is something that is measured in the field. Our customers have fed back to us they are 99 percent up time. If you look at the automobile industry with robots installed on a line, if you are not looking at a robot with that up time, you don't have a product to sell.

Mr. VOLKMER. Do you agree on that?

Mr. BEECHER. Yes.

Mr. VOLKMER. Thank you, Mr. Chairman.

Mr. GORE. Mr. Rossol, just a couple more brief questions, how much of GM's automobile manufacturing capacity will be robotized by 1985?

Mr. ROSSOL. Our numbers show that we will have 14,000 robots in production by 1990. By 1985—do you know?

Mr. BEECHER. 5,000.

Mr. GORE. 5,000 per year?

Mr. ROSSOL. No; a total of 5,000 robots installed.

Mr. GORE. What percentage of your auto manufacturing capacity would that represent?

Mr. ROSSOL. Well, we don't have any real numbers for you except to say that that number of six is considerably high.

Mr. GORE. Six what?

Mr. ROSSOL. Six people.

Mr. GORE. That is too high?

Mr. ROSSOL. Yes; by a factor of three at least.

Mr. GORE. Which means you think one robot replaces two people?

Mr. ROSSOL. At most.

Mr. GORE. What about 1995?

Mr. ROSSOL. We don't have any numbers that far in advance.

Mr. GORE. Is it fair to say that the percentage of your manufacturing capacity will be robotized by 1995 or 2000, that it will greatly exceed the percentage that is not robotized?

Mr. ROSSOL. It is fair to say that it will greatly exceed the percentage that is now robotized.

Mr. GORE. Do you—would it mean there would be some robotization on most or all of your assembly plants?

Mr. ROSSOL. We think assembly robots represent the biggest potential new robot market. Currently, they are not greatly used for assembly purposes.

They are used for spotwelding and other simpler applications. We think in the future, there will be assembly robots that we will use.

Mr. GORE. I know you have given a lot of thought to this, and I hope you can help the subcommittee in the exploration of this question, you have got to anticipate a lot of jobs being lost as a result of robots being introduced into the manufacturing process.

I know it is a sensitive subject, but one that the whole country is going to have to deal with. I don't want to put you on the spot, but if you would help us grapple with the problem.

How does GM grapple with it?

Mr. ROSSOL. We understand the question—it is a difficult one. We do spend a substantial amount of time looking at it.

We believe the relationship between automation and unemployment is tenuous at best. Our thinking is that the introduction of robots may well increase, rather than decrease, the number of jobs doing two things—making us more price-competitive and by helping us produce a higher-quality product.

Mr. GORE. Now, does that mean that you expect that the people, all of the people whose jobs are going to be done by robots will continue to be employed by GM?

Mr. ROSSOL. We have not, up to this point, seen any people lose their jobs because of robots and we don't expect it to happen in the future because of the relatively gradual introduction of robots.

Mr. GORE. Well, I wish we had other manufacturers here so we wouldn't all be exploring it within the context of GM and I don't want to put you on the spot, but I wonder if that is really an accurate analysis of what has happened, that no jobs have been taken by robots.

If one looks at the number of people laid off by GM, by your competitors as well, but if you look at the number of people laid off by GM and you look at the introduction of robotic manufacturing in the Japanese auto plants and the prospective reopening of some facilities that did employ lots of people with robots instead, can you really say that no people have been replaced by robots in GM?

Mr. ROSSOL. Again, I am a little out of my area of expertise, but the question I think that should be asked is, Is there unemployment because of automation or because of the lack of automation? I don't know if the answer is clear.

Mr. VOLKMER. Mr. Chairman.

Mr. GORE. Yes.

Mr. VOLKMER. If I can interrupt just to put it on a little personal note, at the present time, GM is building one of their newest plants at Wentzville in my district and it will have a lot of robots, as I understand it, and I am welcoming that because I would rather have a plant with a robot than not have a plant with robots.

I think that is part of it.

Mr. GORE. I think that is a useful addition to the record and I currently have a large plant being built in my district by Nisson that is utilizing a large number of robots as well.

We welcome that facility, too.

Mr. ROSEN. Mr. Chairman.

Mr. GORE. But the point I am getting at is this, instead of beating around the bush, it just seems to me reasonable to expect, however much we want to fuzz it over or pretend that for every job lost, there will be another one created, the fact is that the introduction of robots in a manufacturing operation like GM is probably going to mean elimination of a lot of jobs.

It may be a companion need by creation of an equal or greater number of jobs in other parts of the economy; it may be that a large percentage of those people whose jobs are affected can be employed by General Motors doing different tasks, overseeing the robots, whatever.

But to the extent that it is reasonable to suppose some jobs will be eliminated, does GM anticipate a retraining effort to anticipate that or what?

Mr. ROSSOL. Yes, we are aware of the problem, we are working with our people. We anticipate some retraining, and do whatever we can do.

Mr. GORE. Have you encountered any hostility from your work force as a result of the introduction of robots?

Mr. BEECHER. The answer to that question is no, we have not experienced hostility. I would like to address the previous question about the retraining.

We have had training programs for a number of years in various areas, obviously. We have programs in retraining for the application of robotics which continually grow more elaborate.

We have several rather sophisticated installations in several of our plants to train people in the use of robots and in the repair and care of them.

In other words, training has been underway for some time and we foresee a much higher growth in that area.

Mr. GORE. Thank you. I don't wish my questions to appear hostile and I will say to my colleague from Missouri, I agree absolutely that we have got to facilitate this trend rather than fight it.

Other countries are going to do it and we are going to lose out if we don't adopt the most modern techniques available.

The point I am making is large employers and other employers have to plan ahead to take care of the people who are most certainly going to be displaced in some numbers.

Mr. SCHEUER. Mr. Chairman, if I may add something. I think you have total unanimity here that we have to move into this area. We have no alternative.

What we are trying to do is anticipate some of the problems and roadblocks and see if we can't defuse them.

Taking the automobile industry, you have lost about 300,000 workers, between 300,000 and 400,000 workers now unemployed as a result of plants closing, as a result of lessening demand for this period of time we are going through, and probably as a result of some degree of automation, cybernation, robotics, whatever.

Assuming that the day, hopefully soon, that the automobile industry picks up, and assuming it does become competitive, more competitive than it is now, assuming that at some future date, more than half the cars bought in the State of California are not foreign cars; and assuming that they are now up to speed and assuming that there is a further introduction of robotics, what percentage of this 300,000 to 400,000 people who are unemployed will be brought back into the industry?

What I am trying to suggest is that I agree, looking at Japan's experience, it is quite possible that robotics increases unemployment, but getting it down to the personal level, me, there are some people who, through the introduction of robotics, are disadvantaged and others who are advantaged, and the guy that gets fired may not be the guy who is taken on to one of the jobs that are increasing global competitiveness.

So looking to the roadblocks, what will happen to those 300,000 people or even over the fairly long period when the industry gets back its muscle tone and what do we do about the profile of that industry if it looks as if there is a significant number of them—I don't want to put words in your mouth—but if the answer to that 300,000 is that most are not likely to be reemployed, what do we do about the profile of that typical worker who is unemployed and who is being disadvantaged and who is not likely to be advantaged?

What do we do to get him back in the mainstream and include him in on this surge of progress?

Mr. GORE. Mr. Rosen?

Mr. **Rosen**. I think we have been concentrating a lot of time on looking at the motor industry and I would like to make a few comments, what my crystal ball tells me.

I don't believe we are going ever to get back to 10 or 12 million cars a year in this country again. I think it is a mature industry. I know you folks from General Motors don't agree with that, but that is my belief.

I think that the available cars from all the motor car industries all over the world that are competing are going to have much more capacity to produce motor cars than can be used by the general public at the prices that they are going to sell them at.

On the other hand, what do you do with all the huge plants, all the productive facilities, all the skilled people—and they are very skilled—some of the best work force in the world.

I have a crystal ball suggestion about that. These companies are going to have to make other products and maybe the products are going to be robot based. We have only been talking about replacing people in our industries with robots to manufacture goods.

We may follow the example of the agricultural industries where 4 or 5 percent of our working populace produce all our food and then some. It may happen that way in the manufacturing industries.

All the other people are in services, medical, sales, distribution, communications, so forth.

Mr. **Gore**. Government.

Mr. **Rosen**. Government.

Those aren't services.

Mr. **Gore**. We will discuss striking that from the record.

Mr. **Rosen**. Well, I have a feeling that you are going to see robot technology begin to enter the service field perhaps within 4 or 5 years, and require an enormous production of extra things that don't exist today, but will exist.

There is no reason why General Motors, that can produce a car for $5,000 to $10,000 can't produce a beautiful robot for $1,000 to $5,000, a simple one, that can be very useful other than in the manufacturing industries.

It is my prediction that they are going to survive, that is, the car industries, and the jobless people are going to be put back to work but change what they produce. They won't produce motor cars.

Mr. **Scheuer**. Thank you very much.

Mr. **Gore**. One followup question; General Motors recently announced its intention to purchase 200,000 Isuzu automobiles for its U.S. market.

Is it fair to conclude—this goes back to your statement that what costs jobs, robotics or the failure to install robotics—to what extent did the Japanese advance in installation of robots influence that decision?

Mr. **Beecher**. I am not sure I understand the question, sir.

Mr. **Scheuer**. Well, this relates to the relationship between robotics and job loss. The larger question is if one country doesn't do it, another one will, and the desire to get away from looking at the problem just within the confines of the United States; is it fair to conclude that GM's decision to make this large Isuzu purchase arrangement was at least in part a result of the fact that the Japanese companies were further along in the installation of robots and their manufacturing facilities and as a result, it was more profitable and efficient for GM to get them there as opposed to here?

Mr. BEECHER. I think the most meaningful answer to that is that I, for one—I am sure Mr. Rossol, also—are not privy to that decisionmaking process.

Mr. GORE. Maybe it is an unfair question. I won't pursue it.

Let me——

Mr. SCHEUER. May I ask one further question?

Mr. GORE. Yes.

Mr. SCHEUER. Mr. Rosen, I asked you what percentage of these 300,000 people who are unemployed now, are going to be reemployed by that industry as we say in my district, irregardless of what they produce?

OK? What percentage of this—I am asking you to look at the profile of those 300,000 people in terms of their literacy skills, their numerous skills, ability to read simple job instructions, ability to adapt?

I hope I am overstating the problem and not understating it, but looking at the profile of those who lose their jobs, what percentage of them are going to be reemployed producing cars or producing robots or produce whatever that industry will produce?

They may produce telecommunications, I don't know, a lot of things. I am thinking of the unemployment and I am thinking of the lifetime employment prospects of the young people, particularly, who have been left off.

What are their prospects? How many of them will the industry likely take back, absent any intervention by us, by Government, in retraining, upgrading of skills and is there a role for Government to help?

Mr. ROSEN. There is only one thing one has to know, Mr. Scheuer, and that is how soon our car industry can get back from the 5 million cars up to somewhere where they were before, because in the near term, it will be zero if they can't increase their sales and marketing of the cars.

Mr. SCHEUER. I am asking you to assume they get back to that level of productivity or they produce something else.

Mr. ROSEN. In the near term, the next 10 years, most of them, if you get back to the same levels of sales, I think most of them. Automation won't remove enough people from the working rolls.

The key thing is how many cars are going to be sold in this year made by American manufacturers.

Mr. SCHEUER. Or how many robots are sold?

Mr. ROSEN. The number of robots that can be manufactured in this country in the next 5 years is very limited. No companies, not Cincinnati Millicron, Unimate or any of the new companies can suddenly increase their robot production overnight, they can't. It takes years to double up or triple up production.

Mr. SCHEUER. You are suggesting, as the automobile industry comes back selling to the public——

Mr. ROSEN. All of those people will come back.

Mr. SCHEUER [continuing]. Cars, robots, whatever?

Mr. ROSEN. I am not saying it will come back to 12 million production, though.

Mr. **Scheuer**. But assuming they will be back at work, they will be using that plant and equipment in some way.

Mr. **Rosen**. Yes, I think so.

Mr. **Scheuer**. Will they absorb the 300,000 people that are out of work?

Mr. **Rosen**. I think so.

Mr. **Gore**. The answer is we will have to have a massive job retraining.

Dr. Sanderson?

Dr. **Sanderson**. I don't feel I am an expert on the manpower problem, but there were a couple of questions brought out in the program that I would like to have the panel elaborate on.

One of the major points was basically there are two areas of interaction where there is a recognized need for greater research.

One is in what I would call the basic components such as sensors, control systems, programing languages for the computer; another has been a statement that there is a major shortage of people who are really expert in systems, and in application of robots as part of a total manufacturing system.

The universities that we are familiar with are very active in many engineering areas looking at components.

Mr. Rosen named a few institutions that were active and very creative in the systems area. Most of those universities—at least the ones that I am most familiar with—have substantial university-industry collaborative programs, in which industry is actively working with the university to provide the scale of environment in which a system program can be developed.

To what extent do you think industry is going to actively expand its support and interaction with the universities in this area of systems development?

Mr. **Radeke**. That is a difficult question. I certainly can't speak for all industry. Certainly from our viewpoint, we have expanded that on a continuing basis and we have even more aggressive plans in the future.

But when we look at the applications in systems, there are two pieces that have to come together. One is the process involved, whether it is metal cutting or joining of metals by spot-welding or arc-welding, one must understand the process being addressed first and then, second, how does the robot, how can it be applied to that process.

There are very few universities that I know that are addressing that type of training at this point.

We do see some training just beginning and when I say "just beginning," I mean within the last 6 months at the vocational school level, not at the engineering level, but it is a down-to-earth, pragmatic "I-am-going-to-use-this-technology" type of approach.

Mr. **Gore**. Any other witnesses?

Mr. **Rosen**. There is damned little, really, in terms of the size of the problem. All the industry-university arrangements can be counted on one hand or two hands, at most.

Yes, they are doing excellent work and they are growing, but the effort has grown from practically nothing to a very, very substantial effort in that field in just a few years.

There are not many Carnegies, not many Stanfords, or MIT's. The size of the problem, you really need an order of magnitude more of that kind going on.

I can't say for sure that there will be the capabilities in the smaller universities that are just beginning to attract that kind of money and support from industry. There has to be a start.

In most cases, graduate schools of these universities have one or two professors who get interested, and they try to get grants from your organization—(NSF)—and from the DOD and that is how they begin. They then attract students and faculty and so on. Very often, they have no facilities.

Even at Carnegie you have to walk around a whole building to see the different projects. The program is not well-centralized; it is hard to acquire buildings and other facilities, let alone robots and other expensive equipment, to get going. So I say there is an order of magnitude less than desired for what is required for this kind of industry-university cooperation primarily because we don't have enough universities that have initiated programs.

Mr. GORE. Mr. Rossol?

Mr. ROSSOL. We work through grants or research work at Stanford, MIT, SRI International, Rhode Island, and a number of other places, and we will continue to do that work.

That may not be as much as Dr. Rosen would like, but we do a substantial amount.

In addition to working closely with a number of universities, we also hire professors as consultants. We get them involved.

Mr. GORE. Thank you very much.

Dr. Chern.

Dr. CHERN. Let me touch on a few points that have been raised.

Let me particularly mention what I call the technology infrastructure. This was not explicitly raised, but the argument goes something like the following.

If you really want to encourage basic research, say a 10-year time scale, the question could be posed that what would happen to the results of that research?

Are they likely to be picked up by other countries, Japan, West Germany, and others, and result in new products marketed by those countries?

Now, the answer in this area is interesting. What one has is a sophisticated technology infrastructure which has arisen in robotics.

There are a number of user and supplier industrial companies which are coming into the area. These companies have rather sophisticated research capabilities and existant R&D groups such as, Cincinnati Millicron, Unimation, IBM, General Electrics, GM, and others.

So you have a unique situation here where there exists the group which will make the machines and the group which will use the machines, as well as possibly make them, available and eager to really draw on the information which is to be developed.

Now, what is interesting is the fact that technology—by that I mean knowledge, understanding of particular things—is best transferred through people and there the role of universities becomes critical because if we are going to develop this type of research, there has to be a significant increase in the number of students that are involved in this in the universities, and will carry the knowledge into industry.

Now, you have coupled with this what is sometimes called the computer culture, a great interest on the part of the undergraduates, as you heard, and graduates in the use of the computer. The computer is going to play a central role in future intelligent robotic systems. So you have a nice system developing where Government-sponsored R&D in a 10-year time scale will propogate through to the industry in terms of products.

So I wanted to mention that explicitly.

Now, one comment. The business about systems of cooperating manipulators. In all fairness, one should say the following, when one asks does one have systems of cooperating manipulators, what you mean is can you get two or more manipulators to interact in real time doing something and modify their operations based on what they find? The answer is I don't think that exists today.

There are significant problems in one manipulator talking to another. You can approximate that problem and it's been done in clever ways. You can divide the work space into two parts and one arm stays in one part of the work space and the other in the other and they cooperate, but they don't cross the boundary.

There are other techniques that one can use.

But the general problem of you taking your two hands and working on something, and based on what is happening, the other arm automatically interacts, that has not been solved.

Except in rather limited circumstances, maybe.

One comment on the robot replacing end people. That is really a difficult problem in the following sense. A robot doesn't replace a person or two people or six people.

A robot is a very limited capability device. People are not.

People have all sorts of sophisticated sensors so when a human being does a job, he is using his eyes, hands, touch, all sorts of operations.

That does not occur when you use a robot. You have to really pre-plan the kind of operation. You have to recognize the fact you have to think it through as you have never done it before.

You can't wave your arms at a robot and tell it do what the guy on the line there is doing. It doesn't work.

You have to very explicitly today program that robot for all contingencies. So it is in a sense fictitious except on the basis of an ROI-type calculation, to say, I can have these robots do the following and this is what the costs will be. But they don't replace people in that particular sense.

I think that is all.

Mr. **Gore**. Thank you, that is a very helpful addition to the report.

Dr. Strauss.

Dr. **Strauss**. I would like to ask a question based on the hearing's outlined topics, that is, the first question limitations of present-day robots in relation to industry needs; and what robot capabilities are needed to allow you to penetrate the market.

I would like to pick a specific industry, machine tool industry. What we are seeing is the simple blades and milling machines are coming from places like India and Hungary, the larger machines coming from Italy and Japan, for example.

One problem is why hasn't the machine tool industry automated?

For example, right across the river from Cincinnati, there is a Japanese corporation with an automated machine tool factory which will make machining centers. Will Cincinnati Milacron be able to compete with the foreign machine tool company across the river without robotizing its own plant, and what will happen to the machine tool industry since we seem, for lack of capability of competing with the Third World countries in the central machines and the Europeans and Japanese in the sophisticated machines?

Mr. **Gore**. We bring these guys in to ask the questions and we are here to ask you to tell him the answer.

Mr. **Radeke**. Yes.

It is a complex question, but let's address it.

First, the import of Japanese machine tools are primarily the lower cost units, but we see a trend in the more expensive machine tool areas. We think that will happen.

There are several issues we have to review, one is obviously our company has produced midrange-and-up type of equipment. I think if you look at our more recent product introductions, they are more down the line, as opposed to up the line, not necessarily in performance, but certainly in size.

I think there is no question that we have to robotize and make our operations automatic.

Let me just go back to that one particular Japanese company that you mentioned to give you a feel for what really occurred there.

I happened to visit it, the one you refer to is Yamisaki, and I went through their facility with the president of their company and what they found when they went to automation, the parts they selected which were machine tool bases, specifically in that limited range, although that represents a large part of the product, is that they could not do it.

They found out that they needed something like 600 different tools and there was no way to design any system automatically to manufacture that product. They then dedicated a large portion of their engineer staff to promptly redesign that portion of the product to allow it to be automated.

I think the thing we have to look at when we talk about applications is not only how you process it, but how is the design done to aid the process?

When we look at that issue, it is one that is not very simplistic, saying "I will automate this plant". Certainly those are very gut-level types of actions. They are actions that are current in our industry, certainly within our company.

If you don't do those things it is clear no matter how much you automate or try to automate the process, if the product is not designed to take advantage of the automation you are still in a no-win situation.

The answer is absolutely those are the directions we are going. That does require a great deal of capital, not only in the sense of money, but human resources, to accommodate those problems.

Dr. **Strauss**. Thank you.

Mr. **Gore**. Do you have other questions?

We are running short on time, but if you have another quick question, Dr. Sanderson?

Dr. **Sanderson**. Just one quick one and I think it was prompted by my own visits to some of the Japanese robotics factories and a comment made by one of the earlier witnesses. The comment was that by the time the Japanese put a robot on the market, they have used it for a number of years, know its strengths, weaknesses and know how to design a product so the robot can manufacture it.

In that sense, maybe General Motors is in a better position than Cincinnati Milacron to make a major effort in this direction.

But the other thing that impressed me was the dedicated move toward a fully automated factory which Fujitsu Fannon, for example, had in their own plants.

I am not aware of any similar move towards the automated factory in the United States. That may be beyond the current capability, but that, in fact, does force one to begin to think about designing for manufacturing, the types of actual sensors needed and provides a feedback into the system which the Japanese seem to be generating and we are not.

I don't know who would like to comment.

Mr. **Radeke**. I happened to visit that plant, also.

I think there is something you have to look at in reviewing the automation of factories. I think Paul Aron's put his finger on it accurately in the previous testimony.

But in the Japanese production, they take a very pragmatic approach. They rate their speeds and feeds where they get into production like the auto industry which says the issue is how many parts do I put on the floor that are good parts per shift, as opposed to how many seconds it takes to produce this part?

It is a totally different way of viewing the problem. Those systems, and I certainly do not in any way mean to detract from their capability and their capacity for producing good solid products, certainly they are not ultrasophisticated systems in the way we would view them.

There is no question that that is the direction they are going. They are doing heavy work in the area of sensors to be incorporated. But what they did not do was say "I am going to wait for the final panacea before taking my first step."

They have taken a pragmatic approach and I consider a successful approach.

Mr. **Gore**. Mr. Rossol, Mr. Beecher?

Mr. **Beecher**. No, sir, I agree with that entirely.

Mr. **Gore**. Well, thank you very much, gentlemen.

I appreciate your testimony. The subcommittee thanks you. Thank you very much.

Mr. **Radeke**. Thank you very much, Mr. Chairman.

Mr. **Gore**. Our final panel is Dr. Daniel Berg of Provost for Science and Technology at Carnegie-Mellon in Pittsburgh; Dr. Bertholt Horn with the Artificial Intelligence Laboratory in Cambridge, Massachusetts; and Dr. Delbert Tesar, director of the Center for Intelligent Machines and Robotics, Mechanical Engineering Department of the University of Florida in Gainesville.

Dr. Berg, we would like to begin with you. I notice several references have been made to Carnegie-Mellon already, you may wish to correct or modify some of those, but we are most interested in your testimony.

Please proceed.

STATEMENTS OF DR. DANIEL BERG, PROVOST FOR SCIENCE AND TECHNOLOGY, CARNEGIE-MELLON, PITTSBURGH, PA.; BERTHOLT HORN, ARTIFICIAL INTELLIGENCE LABORATORY, CAMBRIDGE, MASS.; AND DELBERT TESAR, DIRECTOR, CENTER FOR INTELLIGENT MACHINES AND ROBOTICS, MECHANICAL ENGINEERING DEPARTMENT, UNIVERSITY OF FLORIDA

Dr. **Berg**. I hope I have time to rebut everything that was said. Thank you, Mr. Chairman, and members of the subcommittee. I am Dan Berg, provost at Carnegie-Mellon. I am also professor of science and technology and cofounder of our own Robotic Institute. Perhaps most importantly, I am an active researcher in the sensory part of our institute's work.

I want to make just a few points based on our experience.

First of all, the kind of robots that we work with at our university are the intelligent robots, what we call the see, think, and act robots. They have sensory capacity; they have the "ability" to think; that is, they can take the data that the sensors have accumulated, and can make some sense out of it. They can make some perception of what is going on, and can actually make decisions based on the information they receive. Based on the decision, there will be an action on the part of the robot. With some of our major advanced robots, the robot will actually learn from the action it took whether that action made sense; it will put it in its data base and remember it for the future.

Now, this kind of robot with sensory capacity does not necessarily have to be an arm, nor does it have to be an R2D2 kind of robot. That is, the sensing, intelligence, and action functions can be separate. It can be a distributive robot. The sensor can be in one city, the intelligence can be in another city, and the action can take place in yet a third city thousands of miles away.

To highlight and respond to the subcommittee's questions, the areas of basic research that we think are vital include: artificial intelligence techniques, primarily in the areas of knowledge representation and acquisition; planning and problem solving, model analysis, and use interphases; contact-sensing and recognition on the part of the robots; autonomous and semiautonomous rover robots for working in hazardous environments; and robotic approaches to the assembly of batch-produced parts and materials processing and manufacturing.

From a different perspective, basic research is needed on the societal impacts of and policy issues surrounding robotics. In that regard, I do want to state that in combination with our Robotics Institute, we recently established an industry supported center at Carnegie-Mellon which has the function of bringing together our engineering and public policy groups, our social scientists, business school, et cetera, to focus on the societal impacts of and policy issues surrounding robotics and industrial automation.

To turn to the question of the role of universities, as we all understand, there are a variety of different kinds of universities. I think perhaps all of them do play a role in the training and education of a variety of people, some technical, some scientists and engineers, some managers, some social scientists, and the public in general.

As an aside, I want to point out in response to what was said before that at Carnegie-Mellon, we have established a dual option in manufacturing in belated recognition of a great lack in the educational process. In our mechanical engineering department, we have established an undergraduate manufacturing option. At the same time, in our business school, we are providing an option in manufacturing to our master's students.

The universities fulfill other roles besides those of training and education. Clearly, there are a variety of universities involved with research, a topic which we will discuss in more detail later. Another role, one that Dr. Chern touched on, involves technology transfer. CMU has found that effective robotics research requires not only Federal, industrial, and internal financial support, but also the active operational involvement of sponsors. This latter need derives from the necessity for workplace testing of ideas and developments evolving from our research. Consequently, we have found it to be absolutely necessary to involve industry in this technology-transfer mechanism, not only because industry is a source of resources, but also because they are a test bed for the kinds of things we are working on.

At CMU we have industrial people spend time at our Robotics Institute and have our researchers spend time at industrial sites. It is really more of a partnership in much of what we do, rather than the normal grant arrangement. Our industrial agreements also reflect several levels of cooperative arrangements with industry and with other significant supporters of the research. We have in some cases given up patent rights and software rights to industrial funders. At the same time, in order for the university to function in its proper mode, the industrial groups have let us maintain the rights to publish the material we develop in this work. Consequently, we, as a university, think we have retained what is crucial to us, and given to the industrial group what is crucial to them.

Finally, with regard to the question of the role of the Government, I think the role is multifold. I think, clearly, just as this subcommittee is serving a very useful function in creating public awareness, understanding and support, I think the Federal Government can clearly play a role in leadership, in research and development strategy, and in grants and contracts to support key areas of research. Also, I think the Federal Government can play a crucial role in establishing public policy and focussing on societal issues. I want to support the point that I believe was made this morning by Congressman Scheuer, that it is absolutely critical in this country that we have a scientifically and technically educated citizenry. I do not mean scientists and engineers, but I mean a citizenry that appreciates and understands the role of science and technology.

I think I will stop at this point. Thank you.

[The prepared statement of Dr. Berg follows:]

Proposed Testimony of Dr. Daniel Berg, Provost for Science and Technology, Carnegie-Mellon University, before the Committee on Science and Technology, U.S. House of Representatives, June 2, 1982.

My name is Daniel Berg. I am Provost of Carnegie-Mellon University (CMU).

As we've just heard, robotics and advanced information systems can play - will play - a central role in our future. The size, shape and impact of that role is still being determined by the groups represented here today. The research and development needed to support this process requires a long term, coherent, multidisciplinary approach. The university has both the ability and responsibility to develop new technologies, and to step back and look at them whole: to see how they can be developed and implemented, and to explore if they should be. If up until the recent past the potential of robotics has not been realized in the United States, part of the blame must rest with universities in creating neither research centers to produce the new technologies and to explore their impacts, nor training centers to produce the trained work force.

That is not true currently. With government and industry, universities are developing a research agenda and implementation priorities. In the process, we have also explored the most effective way to support and structure our on-going collaborative efforts.

The Research Agenda

The research agenda is a complex, multifaceted one. It includes basic and applied research and the actual implementation of robotic systems. Its potential impact on areas of our lives extends from manufacturing through office automation, undersea exploration, mining, space exploration and medical applications.

In basic research we must investigate and develop

1. robotic related soft and hardware including:
    - artificial intelligence techniques, primarily in the areas of knowledge representation and acquisition, planning and problem solving, model analysis, and user-interfaces;
    - techniques for visual non-contact sensing and recognition on the part of robots, primarily through reflected light sources (infra-red, x-ray and other electromagnetic radiation) and other sensor systems (tactile sensors, laser sensors, acoustic sensors, and chemical sensors);
    - techniques and hardware for autonomous and semi-autonomous robot rovers; and
    - robotic approaches to the assembly of batch-produced parts and materials processing and manufacturing;
2. impact and policy studies, and supporting analytic techniques:
    - to guide technology choice and implementation;
    - to investigate the robotic related problems faced by individuals;
    - to investigate human resource issues in manufacturing;
    - to investigate alternative organizational structure;
    - to identify institutional options and devise policy strategies;
    - to analyze broader economy-wide issues;
    - to study technology, trade and international competition; and
    - to conduct technology assessments of advanced robotic applications.

CMU Robotic Research Priorities

At Carnegie-Mellon University, the priorities of and unifying elements in our robotic research are artificial intelligence, computer science and sensor based systems. Artificial intelligence research began at Carnegie-Mellon in the 1950's with research into the processes of reasoning and decision making. Current research priorities in artificial intelligence include knowledge representation and acquisition, planning and problem solving, model analysis and expert systems. Carnegie-Mellon University's Computer Science Department, one of the top three in the nation, works jointly with the Robotics Institute in the areas of developing more graceful interactions between men and machines in programs approaching natural language, in developing new languages well suited to programming complex processes with multiple machines, and in developing programs that vastly increase the speed of information anlysis. Carnegie-Mellon University's robotic related sensor based systems research involves the development of novel uses of multiple sensors to monitor the environment and performance of machines; and the development of sensor based systems that enables adaptive control of the machines.

It is of vital importance that this research agenda be joined to an educational program that will produce the work force necessary to enhance and sustain it. Engineers, scientists, managers, technicians, policy analysts, and social scientists are needed. Of equal importance is a diversified, skilled labor force to maintain robotic systems. An important part of this work force must be people who, through a combination of sound fundamental knowledge and skills, and hands-on field experience, understand and can manage technological change.

University/Industry/Government Cooperation

It becomes increasingly obvious as we talk that none of us can do this alone. Each of us by ourselves do not have the comprehensive insight, skills, data, analytical tools, and insititutional environment, that will allow us to develop and improve robotic technology, and to anticipate, understand and learn how to manage the economic and social impacts of robotic and advanced information system technologies. Industry has experience in the practical problems of undertaking and managing technological change in the production environment. Industry and labor organizations have their respective experience with the human resource and organizational aspects of implementing these changes. Universities have the technical expertise, the knowledge, analytical tools and institutional environment that are necessary to generalize such specific industry experience into broader understanding. Government has the power to affect public and private sector policies through its own social and economic statistical data and mechanisms for distributing information. To repeat, none of us will be very successful without the others.

What are effective ways to carry out what is inherently a collaborate effort? We at Carnegie-Mellon University have developed both internal administrative arrangements and an external system of linkages that has proven worthwhile. Internally, our key concerns were to create an organization that encouraged collaboration and free exchange between faculty and students and among the disciplines, and that integrated the various functions that had to be performed (basic and applied research, systems development, teaching, and hands-on implementation). To this end, the Robotics Institute was created. Its objectives are to solve fundamental and applied problems of robotics science through scientific and engineering research; to encourage and assist the transfer of robotics from the laboratory to industry; and to train engineers and scientists for the further development of the field. Institute staff include both CMU faculty and full time researchers. The faculty involved are primarily from Engineering and Science, though faculty from the Social Sciences, Industrial Administration and Operations Research also play a significant role. All faculty retain departmental and college affiliation. Departmental and cross departmental courses have been developed that reflect the research on-going at the Institute. Both undergraduate and graduate students study and do research at RI while maintaining membership in the University department from which their degree will be granted.

Externally, our concerns were to create linkages with government and industry that would promote and protect the exchange of ideas, knowledge and experience; that would produce research relevant to the needs of industry; that would be economically fair and potentially profitable to all parties; and that would provide the level and length of support necessary to carry out robotics research. We approach research relevancy and information

The Government's Role

A successful program in robotic research and development will require a nucleus of continuing support around which a long term coherent program of investigation can be built and to which separately funded studies can be selectively added as opportunities arise. We are approaching multiple sponsors in both government and industry for both long and short term funding.

We believe government can be most supportive in achieving our joint goals:

- by creating general public awareness, understanding and support of the potentials of robotics;
- by creating a network of both legislative and agencies policies and regulations that encourage the growth and development of the robotic industry; and
- by providing individual grants and contracts to support key areas of research, perhaps not readily applicable to specific industries or concerning public policy or societal issues.

I look forward to our continuing discussion.

Mr. Gore. Thank you very much. Dr. Bertholt Horn is from the Artificial Intelligence Laboratory in Cambridge.

Dr. Horn, we are most pleased to have you. Please proceed.

Dr. Horn. I am, as you stated, from the Artificial Intelligence Laboratory, which has been engaged in robotics research for about 17 years. There have been many ups and downs in those 17 years.

One of the points I would like to make is that research funding is needed, but we have lost a good number of researchers as a result of the fact we only had three short periods of strong interest in robotics.

Altogether, I would like to make five points. One is that robots are not applied widely, in part because they are not widely applicable. Their current capabilities are limited.

The second point is that further progress is not just a matter of engineering development, not something that can be carried out by modifying an electric motor or attaching a micro processor.

The third point is that there are deep scientific issues we have to raise in robotics. I think the universities can play a role in addressing those scientific issues.

The fourth point is the one I have mentioned, that I feel that only steady support of the basic research can encourage progress in that area.

The final point, I think there should be ways of supporting the development of application of robotics in industry by various mechanisms such as perhaps reform of the patent laws. I would like to review the state of the art in robotics and along with Dr. Berg, point out that the kind of robot I am interested in has three subsystems, one of which is the mechanical factor; one of which is the reasoning part, or planning part; and one of which is the sensors which allow it to adapt to changes in the environment.

It is certainly true that we can do more in applying the technology we already have, but we must make a firm basis for future applications. The kind of things that are being put into use now are things which were developed in research laboratories like SRI-10, 15 years ago.

We have to continue to supply a stream of new ideas and new concepts by working on basic research in the universities. The present day robot as far as the mechanical part is concerned, has a multi manipulator as you saw in the film, which has either electric or hydraulic actuators. Invariably, it has special purpose groups which have to be redesigned for each application.

Control systems are very simple, they are based on traditional industrial control systems. The nature of programing them is typically to teach by showing method, which is fine if all you want to do is have the robot repeat indefinitely the same motion. There are now a few simple programing languages which allow you an alternative means of programing the robot.

On the sensing side at the moment, all we have are simple switches which allow you to take where the part has arrived at the feeder and maybe some scanners which allow you to follow a seam in welding. But the vision side is highly deficient. There is a lot that needs to be done.

As was pointed out earlier, vision is a very difficult process. And it is certainly going to take some time to tackle the deep issues of inverting the process of imaging the three-dimensional world on to the two-dimensional image.

The current research area we are engaged in, first on the manipulator side, include designing manipulators for assembly. Present day manipulators are very good at picking up a part and putting it down somewhere else. For this they need to have position and velocity controls.

In assembly, the parts interact and a force is created. What is more important than position control is control of the appliance, how the manipulators adjust to the forces created. This has implications for the programing and for the design of the manipulator.

Secondly, we would like to get away from the need to design it for every task. Part of the robot's beauty is that it is supposed to be easily reprogramable for a new task. Yet, at the moment we are faced with making a new gripper for every job. So we and other universities are interested in studying dextrous multifingered hands with tendons much like our own hands.

One of the shortcomings of today's robots is that they are too slow, was mentioned by a previous witness. Part of the reason is that the control systems that are used are very simplistic. They are not too slow because the strength of the materials is not there, they are not too slow because the motors are not powerful.

They are too slow because the control systems fail at high speeds. We have done some work on improving that, using computational methods. On the thinking third of the robot, we have been interested in developing systems which can reason about objects and space. At the moment, the way you teach a robot is either to lead it through the motions or to program it by detailed analysis, saying move 1 inch to the right and 2 inches down.

It is clear that this will be an obstacle in reprograming at the end of the year. When a new model comes in you will spend a month just trying to reprogram the manipulator. One way out is to program in terms of the task rather than detailed manipulator motions. You might say test part A on part B. Assuming the computer has representations for these parts, it can then figure out where to pick one part up so it can place it on the other part and also determine its trajectory, where it would not bump into something else.

In terms of the thinking about objects and space is quite hard, even though we have no trouble with it. So it is a little bit confusing.

For example, it is very hard to understand why vision should be hard. We are so good at it. We find the same problem in spacial reasoning. It is quite difficult to teach a computer to think about paths and objects. We also find a need to deal with inaccurate parts positioning. That can be dealt with in a number of ways.

One is to have, giving the compliant manipulator, which has springiness built into it, so it will adjust to a certain degree to inaccurate parts positioning. Another way is to use sensing techniques, in particular vision. As Mr. Rossol pointed out, we have systems which can look on conveyor belts and determine exactly where a part is. Or in our case, we developed a system 7 years ago which allows you to look at a circuit chip and orient it so you can automatically bond the leads to it.

There are yet other methods. For example, if I had this ash tray coming down a conveyor belt, I could alien it simply by having a gage across the belt. As the belt pushes it, it will automatically achieve a certain position of orientation. I can do the same with a manipulator hand.

So in some cases, I can avoid the need for sensing simply by looking at the problem of the interaction of the part with the manipulator.

This kind of scientific approach has been neglected. People have mostly felt that, well, we take a mechanical system, hook up some motors to it, and add several microcomputers and away we go. I think future progress will depend on analyzing the physics of these interactions and of the image formation, then building mathematical models based on that and building algorithms on the mathematical models.

I think that is somewhat obliterated by the typical Businessweek article where it looks like you take your home computer and hook up a vacuum cleaner motor and you have robotics. In fact, we find this a problem in attracting students because they do not yet understand that there is real science to be done in robotics.

Some of the problems we have had in the field related to this difficulty of uneven funding, we have been interested in robotics for a long time. Only in a few spurts have we been able to attract funding. The result is that some of the better people have gone off to do other things.

The result now is that the country has a very small number of knowledgeable people. I think this is one of the big differences with Japan. There are a very large number of people, perhaps not in the most sophisticated technology, but people who are used to working with robots. We do not have that.

A side issue there is that there is a huge salary disparity between the universities and industry, which causes the few people we have to be siphoned off. The few groups which have attained critical mass to do research are being disbanded.

Now we have a number of companies that have perhaps one roboticist who is able to educate management about robotics, but not actually able to do any real research. The relationship between universities and industries I see as follows.

First I think the university is the appropriate place to carry out the basic research, not tied to next year's model. And with the wonderful resource of bright, young students coming in, able to work on these problems.

A second problem we have is in educating students. These will be the future users of systems, and in some cases, designers of systems. The interest is enormous. My undergraduate course which has been going for 7 years has 80 percent enrollment this year. However, six or so universities teaching 60 students each is nothing compared to what we need.

There is a real need to rapidly expand education at more and more universities in this area. We also run short summer courses attended by engineers who are the current users to try to fill the gap. These are also very well attended.

I guess other roles are things like writing textbooks and editing journals. Only recently are there good journals in the field where you do not find yourself looking through 20 different publications to try to find research on robotics.

Industry's role includes carrying out applied research, and identifying real problems for us. In many cases, universities end up working on things which are toy problems, which are not really significant. On the other hand, in other cases we find industry gives us conflicting signals.

For example, the famous bin of parts problem which was mentioned earlier. In some industries, this is considered the ultimate, the most important thing to work on. If you can take a bin which has parts lying on top of each other, all of the same type, say, and you can pick things out of there with the robot, then you have done a great service to them.

Yet other industries say, well, this is not a problem because we can palletize them and keep them precisely oriented. I think it is a little bit a matter of semantics. Namely, if you can throw them all in the box the way we do now for people, you have a cheaper system. Sure, you can palletize them but the pallet will cost you a fortune, and take up a lot of space and not be nearly as convenient.

Another role of industry is to take the methods that have been proposed and see whether they really are robust enough to apply in practice. As was pointed out, we are not really in a position to work on these things. Among other things, students would like to develop theses which are typically more cost-related to research than they are to developing a particular solution.

Interaction between universities and industry is quite strong. It includes visitor exchange programs. For example, at the moment we have a program which we call the "Year of the Robot" where in order to again rapidly increase our research in robotics, we have invited industrial visitors to come in and work with us for a year on problems of mutual interest.

I have mentioned the intensive short courses that we provide, and also Lothar Rossol mentioned the intense consulting interactions between industry and universities which are very useful in keeping us on the straight and narrow as far as working on real problems is concerned. And in some cases, industry of course has helped fund the research.

As far as the role of the Federal Government is concerned, I think the most important is in terms of steady funding of the research. I think that the sort of on and off again funding we have seen in the past is not really conducive to developing the field very well. It needs to be somehow organized and kept at a steady level.

Then, also to encourage industrial application, there are many ways to do it. Obviously I am the wrong person to talk about it, but many things come to mind. Obviously there are tax incentives, writeoffs. For example, at the moment most of the inventions in the field are hidden, buried in side products because there is no way of protecting them in the patent field. Therefore this knowledge is not fully developed.

There are many cases in which I have come across systems which include really innovative ideas, but I could not use those results because they were part of some proprietary product. If it was possible to patent some such products, I think it would be much better for everyone.

Well, I think that the point I want to end on is my feelings when I visited Japan. I found that in terms of share numbers they are ahead. But what was the most startling thing to me was the way we have embraced this technology. They are not arguing about it any more.

I have spent years arguing about it. They have just decided let's go with it. There is a spirit out there that you go ahead and even applied in cases where it does not make economic sense right away, just so you can learn.

In many ways they have gained an advantage on us just because of that. Thank you.

[The biographical sketch and attachments of Dr. Horn follow:]

1. Full Name: Berthold K. P. Horn

2. Date of Birth: 1943 December 8

3. Citizenship: German

4. Immigration Status: Permanent resident

5. Education:

School	Degree	Date
University of the Witwatersrand	B. Sc. (Eng.)	Dec. 1965
M. I. T.	S. M.	June 1968
M. I. T.	Ph. D.	June 1970

6. Principal Fields of Interest:

(1) Machine Vision & Visual Perception.
(2) Machine Manipulation & Productivity Technology.
(3) Spatial Reasoning & Expert Problem Solving.

7. Employment prior to M. I. T.:

Employer	Position	Beginning	Ending
University of the Witwatersrand	Junior Lecturer	Jan. 1966	Aug. 1967
University of the Witwatersrand	Lecturer	Jan. 1971	Dec. 1971
Perseus Computing	Software Manager	Feb. 1972	June 1972

8. History of M. I. T. Appointments:

Rank	Beginning	Ending
Instructor (Mathematics)	Aug. 1970	Dec. 1970
Research Associate	July 1972	Jan. 1973
Assistant Professor	Jan. 1973	June 1976
Associate Professor (without tenure)	July 1976	June 1979
Associate Professor (with tenure)	July 1979	---

9. Consulting Record:

Firm	Beginning	Ending
Randfontein Estate Mining, R. S. A.	Nov. 1963	Feb. 1964
Institute of Oceanography, R. S. A.	Dec. 1965	Aug. 1966
H. H. O. Civil Engineering, R. S. A.	Dec. 1966	May 1967
Aircraft Operating Company, R. S. A.	Jan. 1967	June 1967
Anglo American Corporation, R. S. A.	Apr. 1967	June 1967
University of Sussex, U. K.	Sep. 1972	Nov. 1972
National Retail Food Stores	Oct. 1972	Mar. 1973
Schlumberger	Dec. 1972	Mar. 1973
General Motors Research Laboratories	Dec. 1974	---
Mass. General Hospital	June 1975	July 1976
Texas Instruments	July 1975	Jan. 1976
Applicon	Sep. 1975	Nov. 1976
Butler	Jan. 1976	Dec. 1978
Federal Highway Administration	Apr. 1977	June 1977
Information International Incorporated	May 1977	Nov. 1977
N. A. S. A.	June 1977	Sept. 1979
Optronics	Dec. 1977	Mar. 1978
Jet Propulsion Laboratory	Nov. 1978	Nov. 1979
Texas Instruments	July 1979	Dec. 1979
Elscint	July 1979	July 1981
Textron	Feb. 1980	Mar. 1980
Stocker & Yale	Nov. 1980	Nov. 1981
National Enterprise Board, U. K.	Dec. 1980	Mar. 1981
ASEA	Feb. 1981	Dec. 1981
Automatics	Sep. 1981	---
Bridgeport	Oct. 1981	---

10. Awards Received:

Award	Date
First Prize: Individual Student Project. South African Association for the Advancement of Science.	Dec. 1961
Gold Medal & Scholarship: Best non-mining Student. South African Chamber of Mines.	Dec. 1965

11. Current Organization Membership:

Organization	Offices Held	Dates
Society for the Protection of Wildlife	Jan. 1966	---
SIGMA XI	Aug. 1968	---
S.W.A. Wissenschaftliche Gesellschaft	Jan. 1979	---
Boston Mycological Society	Sep. 1981	---

12. Patents and Patent Applications Pending:

1. B. K. P. Horn, "Tomography X-ray Detector," U. S. Patent 4,110,621. 1978 August 29.

Publications of Berthold K. P. Horn:

1. Books

(1) P. H. Winston & B. K. P. Horn, *LISP*, Addison-Wesley, Reading, Massachusetts, 1981.

2. Papers in Refereed Journals

(1) Horn, B. K. P., "Fitting non-harmonically related sinusoids" Appendix I of "Recent Developments in Tidal Analysis in South-Africa," by A. M. Shipley, *International Hydrographic Review*, Monaco, April 1967, pp. 66–70.

(2) Horn, B. K. P., "Artificial Intelligence — a little vision on the real world," *Systems/Stelsels — Bulletin of the Computer Society of South Africa*, Johannesburg, Vol. 1, No. 4, March/April 1971, pp. 10–15.

(3) Leigh, R. A., Van Blerk, P. J. P. & Horn, B. K. P., "Lymphocytic Infiltration in Bladder Cancer," *South African Medical Journal*, Capetown, February 1973, pp. 192–194.

(4) Horn, B. K. P., "A New Machine Organization — something to look forward to," *Systems/Stelsels — Bulletin of the Computer Society of South Africa*, Johannesburg, Vol. 3, No. 4, July/August 1973, pp. 6–12.

(5) Horn, B. K. P., "The Legacy of a Poor Formalism — a tree is not the key," *Systems/Stelsels — Bulletin of the Computer Society of South Africa*, Johannesburg, Vol. 3, No. 5, September/October 1973, pp. 6–10.

(6) Horn, B. K. P., "Determining Lightness from an Image," *Computer Graphics and Image Processing*, Vol. 3, No. 1, December 1974, pp. 277–299.

(7) Horn, B. K. P., "A Problem in Computer Vision: Orienting Silicon Integrated Circuit Chips for Lead Bonding," *Computer Graphics and Image Processing*, Vol. 4, No. 1, September 1975, pp. 294–303.

(8) Horn, B. K. P., "Circle Generators for Display Devices," *Computer Graphics and Image Processing*, Vol. 5, No. 1, June 1976, pp. 280–288.

(9) Hinder, R. A., Horn, B. K. P. & Bremmer, D. G., "The Volumetric Measurement of Gastric Emptying and Gastric Secretion by a Radio-Isotope Method," *The American Journal of Digestive Diseases*," Vol. 21, No. 11, November 1976, pp. 940–945.

(10) Horn, B. K. P., "Understanding Image Intensities," *Artificial Intelligence*, Vol. 8, No. 2, April 1977, pp. 201–231.

(11) Horn, B. K. P., "Rational Arithmetic for Minicomputers," *Software Practice and Experience*, Vol. 8, No. 2, March/April 1978, pp. 171–176.

(12) Horn, B. K. P., "Density Reconstruction Using Arbitrary Ray Sampling Schemes," *Proc. of the I. E. E. E.*, Vol. 66, No. 5, May 1978, pp. 551–562.

(13) Raibert, M. H. & Horn, B. K. P., "Manipulator Control using the Configuration Space Method," *Industrial Robot*, Vol. 4, No. 2, June 1978, pp. 69–73.

(14) Horn, B. K. P. & Bachman, B. L., "Using Synthetic Images to Register Real Images with Surface Models," *Comm. of the A. C. M.*, Vol. 21, No. 11, November 1978, pp. 914–924.

(15) Horn, B. K. P. & Woodham, R. J., "Destriping LANDSAT MSS Images using Histogram Modification," *Computer Graphics and Image Processing*, Vol. 10, No. 1, May 1979, pp. 69–83.

(16) Horn, B. K. P. & Sjoberg, R. W., "Calculating the Reflectance Map," *Applied Optics*, Vol. 18, No. 11, June 1979, pp. 1770–1779.

(17) Horn, B. K. P., "Fan-Beam Reconstruction Methods," *Proc. of the I. E. E. E.*, Vol. 67, No. 12, December 1979, pp. 1616-1623.

(18) Horn, B. K. P., "Hill-Shading and the Reflectance Map," *Proc. of the I. E. E. E.*, Vol. 69, No. 1, January 1981, pp. 14–47.

(19) Ikeuchi, Katsushi & Horn, B. K. P., "Numerical Shape from Shading and Occluding Boundaries," *Artifical Intelligence*, Vol. 16, No. 1-3, August 1981, pp. 141-184.

(20) Horn, B. K. P. & Schunck, B. G., "Determining Optical Flow," *Artificial Intelligence*, Vol. 16, No. 1-3, August 1981, pp. 185-203.

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(1) Horn, B. K. P., "Towards a Science of Image Understanding," *Proc. 5th Int. Joint Conf. on Artificial Intelligence*, Cambridge, Massachusetts, 1977 August 22–25, pg 648.

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THE UNIVERSITY'S ROLE IN THE DEVELOPMENT OF ROBOTICS

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STATE OF THE ART IN ROBOTICS

Industrial robots have not yet fulfilled there apparent promise of greatly improving industrial productivity. Why? The answer is that they are still very limited in their capabilities.

Today's industrial robots are mechanical manipulators consisting of rigid links attached to each other at joints driven by electrical or hydraulic motors. At the business end of the manipulator there is usually a special purpose gripper. Joint angles and velocities are relayed back to simple control systems, one per joint.

The manipulator is taken through a sequence of motions by a person using push buttons on a teaching pendant. These motions can then be repeated indefinitely. More recently, simple programming languages have been intrdouced which provide alternate means of specifying the tasks to be performed.

Sensing of the presence of a part in a feeder may be performed using a simple switch, and the sequence of motions delayed if necessary. The outputs of other such binary sensors may cause the manipulator to follow different sequences of motion depending on the type of part. Special purpose scanners may allow the manipulator to follow a feature on the surface of an object, as is required in seam welding. Images of high contrast between object and background, in which the information is essentially two-dimensional, can be processed by binary image processing systems to determine the position and orientation of an object. In this way, a manipulator can pick a part from a conveyor belt even when it is not exactly in the pre-programmed position.

Typically the industrial robot is limited to repeating exactly the sequence of moves taught, unable to adjust to errors in parts positioning or small errors in its own motion. While suitable for transferring parts from one place to another, it is not good at assembly operations. Present day hands are specialized devices which are usually able to grip only certain classes of objects. Often an industrial robot is also limited by its simple control system to speeds of motion lower than its mechanical structure would allow.

PRESENT RESEARCH AREAS

EFFECTORS:

In parts transfer the ability of a manipulator control system to follow a trajectory through space is of paramount importance. In assembly however the detailed motion after parts meet must be determined by how they conform. In this situation control of forces is more appropriate than control of position. One wants to be able to adjust the springiness or compliance of the gripper. This has implications for the design of the manipulator as well as the system controlling it and the way it is programmed.

A big advantage of the industrial robot is the fact that it can be easily reprogrammed for another task. Something which runs counter to this is that the specialized grippers now used have to be designed afresh for each application. Dextrous multi-finger hands with tendon actuation are needed.

Present day manipulators cannot deal with errors in parts position and must therefore have accurate parts feeding mechanisms. These special purpose devices again run counter to the otherwise easy reprogrammability of robotics systems. One way to deal with uncertainty in the positioning of the parts being manipulated, is to sense where the part lies in the hand. A sense of touch requires more than simple on-off switches however. The tactile sensor must have spatial resolution and be able to measure the forces applied.

For rapid moves, interactions between the rigid bodies constituting the manipulator become important, as do centrifugal and Coriolis forces. Manipulators with one simple control system per joint cannot deal with these effects. The speed of operation is therefore artifically restricted to one which the control system can handle. A manipulator able to perform a move more rapidly can carry out more operations per year and will be correspondingly more attractive to the user.

PLANNING:

Today industrial robots are programmed by specifying their motions. If a different manipulator is used for the same task a totally different program is needed. A great deal of effort goes into specifying detailed motions in terms of distances and angles. It would be much more convenient if these devices could be programmed in terms of the task to be accomplished. The programming languages needed for this are entirely different from the simple ones existing now. It would be very useful if the programming system could carry out some of the spatial reasoning operations associated with path planning for example.

Existing methods also do not provide for the programmed application of forces, since they concentrate entirely on position. For assembly operations the compliance of the arm must be controlled. Another difficult issue is the control of two manipulators cooperating on some task. Often, for example, a fastener, to be used for holding parts of an assembly together, has two parts which can only be brought into position using two manipulators.

One need not always sense where a part is to deal with uncertainty in its postion. One can employ a motion which automatically aligns the part relative to the hand just by sliding the part on its supporting surface. Work is needed to automatically come up with such alignment strategies.

SENSORS:

Measuring the forces when the hand touches an object is not enough. The information has to be interpreted to determine what it implies about the position of the object within the hand.

Vision is our most powerful sense. It is also the most complex. It is not surprising then that only very crude vision systems have been developed so far. The simple binary image processing systems now available work only in very restricted situations. Much needs to be done to further develop methods which allow manipulator systems to deal with uncertainty in parts position. Machine vision also holds promise for certain inspection tasks, such as for surface finish and to check for the presence of a componenet of an assembly.

Systems which reason about the motion of objects through space need to represent these object and the space between them. Sometimes suitable models for the objects can be derived from the computer-aided-design (CAD) systems used to design those objects. In other cases it may be more convenient to develop the model based on showing the object to a machine vision system.

SUMMARY:

While further work is needed on the hardware of manipulators, grippers and sensors, the key problems are in the area of software. The programs cannot be written however until the basic algorithms are developed. This in turn requires a thorough understanding of the physics of the interaction of the effectors and sensors with the environment.

BASIC SCIENTIFIC ISSUES

EFFECTOR:

In order to properly use mechanical manipulators it is necessary to understand how their geometry or kinematics affects their use. It is also important to understand the relationship between the torques produced by the actuators and the forces exerted by the hand on the environment. For control at high speeds, the equations of motion must be developed. The interaction between the hand, the part being held, and the environment must be modelled.

PLANNING:

Methods for representing objects and space in a computer need to be further explored. Motion sequences can then be planned provided the system can reason about the trajectories. Flexible objects will present particular difficulties in manipulation. Systems must be developed which can react in a robust manner to a variety of events not anticipated by the person programming the manipulator.

SENSORS:

In order to extract information form images it is necessary to first understand the transformation from the three dimensional world to the image. Then, under favourable circumstances, one can go about undoing this transformation. The shape of an object may be recovered and its attitude in space. Surface properties and shape may be used in recognition.

Machine vision is difficult. In the industrial automation context however, it is possible to use specialized lighting arrangments and other methods to simplify this task. Thus progress can be made long before we have an adequate theory of how human vision might work.

SOME PROBLEMS

Funding for robotics research has been sporadic. One result is that some researchers went on to other things in the lean years. This means that there are not that many people with more than a superficial knowledge of the research areas. There is heavy competition between the companies scrambling to get into robotics for these people. This creates a huge salary disparity between university and industrial research establishments. It also tend to tear apart the few groups which have become large enough to be effective. Many companies then end up with less than a critical mass. Perhaps they have only a token roboticist who is engaged in educating management rather than carrying out research.

Another difficulty is that it has not become apparent to many that robotics is more than a study of how to hook a micro-computer to an electric motor driving a joint on a multi-link mechanical device. There are deep scientific issues and the methods of physics, mathematics and computer science must be brought to bear.

RELATIONSHIP BETWEEN UNIVERSITIES AND INDUSTRY

UNIVERSITY ROLE:

The university's role is primarily in the area of basic research and education. The long-range effort needed to lay the ground-work for the more applications-oriented research is best carried out away from the immediate demands of next year's product. It is preferable that much of the basic research be carried out in the open, to avoid it being buried by competitive secrecy. There is a desparate need to educate students who will be tomorrow's users and designers of robotic systems. There is a similar need to educate engineers using and designing robotics systems now. Then also, texts must be developed which make information more easily available. This is a little tricky in an area which is changing so rapidly. Research articles should be published in journals dedicated to this area.

INDUSTRY ROLE:

Industry's role is primarily to carry out research oriented more towards applications. The line between what is basic and what is applied research is hard to draw of course. Only industry can identify problems which are really worth solving. Here too, methods which have been proposed can be tested. Often what works in the friendly environment of the laboratory fails to work in the real world. It is in industrial research laboratories where the successful ideas can be transformed into the robust systems which can be put to practical use.

INTERACTION:

Students of robotics courses at universities transfer knowledge to the companies that they are employed by. Similarly, short intense courses can bring the professional in the field up to date. Very helpful in ensuring that researcher in the universities are aware of real problems is a program encouraging visitors from industry to stay for some time. The visitor has the oppportunity to work with bright and eager students during his stay. Another conduit of information to industry is provided by the consulting relationships between individual faculty members and companies. In some cases companies may elect to fund research at a university rather than in their own research department.

ROLE OF THE FEDERAL GOVERNMENT

SUPPORT BASIC RESEARCH:

Steady support of research on advanced automation and robotics will ensure a supply of ideas and people able to improve productivity. There is no substitute for this type of funding.

ENCOURAGE INDUSTRIAL APPLICATION:

Companies should be encouraged to participate in research themselves by means of suitable tax incentives. The application of this new technology should be similarly encouraged. Cooperation in research between different companies should be permitted. It would be advantageous if the patent system was more receptive to methods used in robotics systems. Measures should be taken to encourage the formation of small firms with promising new ideas in the robotics area.

ALSO:

An effort should be made to try and anticipate possible problems created by advanced automation.

STATE OF THE ART IN ROBOTICS

MECHANICAL:

- Multi-link Manipulators
- Electrical or Hydraulic Actuators
- Special Purpose Grippers

CONTROL:

- P. D. I. Control Systems
- Teach by Showing
- Simple Programming Languages

SENSING:

- Limit Switches
- Special Purpose Scanners
- Binary Image Processing

PRESENT RESEARCH AREAS

EFFECTORS:

- Manipulators Design for Assembly
- Dextrous Multi-Fingered Hands
- Imaging Tactile Sensors
- High Speed Control

PLANNING:

- Spatial Reasoning
- Task Level Languages
- Compliant Manipulation
- Alignment Operations

SENSORS:

- Interpreting Tactile Information
- Vision for Alignment
- Vision for Inspection of Surface Properties
- Acquiring Object Models

BASIC SCIENTIFIC ISSUES

EFFECTOR:

- Kinematics and Statics
- Dynamics
- Modelling of Interaction

PLANNING:

- Representing Objects and Space
- Automatic Motion Planning
- Reasoning about Flexible Objects

SENSORS:

- Understand Image Formation
- Recover Shape and Attitude
- Recognition

SOME PROBLEMS

- Uneven Funding Profile
- Lack of Knowledgable People
- Large Salary Disparity
- Not Considered Science

RELATIONSHIP BETWEEN UNIVERSITIES AND INDUSTRY

UNIVERSITY ROLE:

- Carry out Basic Research
- Educate Students - Future Users
- Educate Engineers - Current Users
- Write Text-Books and Edit Journals

INDUSTRY ROLE:

- Carry out Applied Research
- Identify Real Problems
- Evaluate Utility of Proposed Methods
- Bring Laboratory Methods to Practical Use

INTERACTION:

- Visitor Exchange Program
- Intensive Short Courses
- Consulting
- Fund Research

ROLE OF THE FEDERAL GOVERNMENT

- Support Basic Research

- Encourage Industrial Application

ARTIFICIAL INTELLIGENCE LABORATORY

The primary goal of the Artificial Intelligence Laboratory is to understand how computers can be made to exhibit intelligence. Two corollary goals are to make computers more useful and to understand certain aspects of human intelligence. Current research includes work on English-language understanding, learning, common-sense reasoning, distributed problem-solving, expert engineering problem-solving, computer vision and manipulation, manufacturing productivity, computer architecture, human development, and human education.

Professor Patrick H. Winston, Director of the Artificial Intelligence Laboratory, heads the research effort in learning and reasoning by analogy. Professor Berthold K. P. Horn and Professor Shimon Ullman direct work in computer vision. Dr. J. Michael Brady, Dr. John M. Hollerbach, and Professor Tomas Lozano-Perez lead research on computer-controlled, multiple-joint manipulators and other aspects of Robotics. Professor Randall Davis and Professor Carl E. Hewitt work with distributed problem-solving and parallel computation. Professor Marvin Minsky develops general theories of artificial and natural intelligence. Professor Gerald J. Sussman, Dr. Howard E. Shrobe, and Mr. Thomas F. Knight work on the problems of integrated circuit design. Dr. Charles Rich and Dr. Richard C. Waters explore the creation of intelligent programming environments. Mr. Richard D. Greenblatt does research on memory and heuristic control. Professor Seymour Papert leads efforts concerned with education through the use of computers.

The Laboratory's 80 members include 10 faculty, 35 research and support staff, and 30 graduate students involved in research activities funded by the Defense Advanced Research Projects Agency, the Office of Naval Research, the Air Force Office of Sponsored Research, the National Science Foundation, the Olivetti Corporation, the Xerox Corporation, the Jet Propulsion Laboratory, and IBM.

Image Understanding

Professor Horn's group studies the problems associated with the relationship between the shapes of visible surfaces and their gray-level shading. In particular, Professor Horn formulated the image-irradiance equation, which relates surface orientation to brightness values, and he developed the reflectance map, which graphically displays the constraint implied by the image-irradiance equation.

One application of the image-irradiance equation and the reflectance-map representation is centered on the development of albedo maps, in which ground slope and sun position are factored out so that intensity is solely a function of ground cover. A crucial step in this application, the generation of high-quality synthetic images, is difficult because of atmospheric scattering. Professor Horn and Mr. Robert J. Sjoberg have demonstrated that although understanding the effects of the atmosphere is a difficult task, the adoption of even simple models can provide substantial improvement over results obtained with no model. In particular, they have showed how the abundance of shadows cast in mountainous regions can aid in the determination of path radiance. Professor Horn and Mr. Sjoberg are extending the models in order to extract calibration data from multichannel images and from multiple images taken a few days apart.

In general, the image-irradiance equation has an infinite number of solutions, each corresponding to a surface. Thus shading alone is not sufficient to determine a surface uniquely. Working with Professor Horn, Dr. Anni R. Bruss has examined the use of supporting information from silhouettes, edges, and rotational symetry, showing how to arrive at unique solutions in some cases. In particular, she has showed when the images captured by scanning electron microscopes determine surface shape uniquely.

Professor Horn and Mr. Brian G. Schunk continute to investigate the use of the image-irradiance equation in determining with the instantaneous positional velocity field which is generated on the image plane by moving in a textured environment. One important application is in navigation where it is desirable to determine camera motion from noisy image sequences. Professor Horn and Dr. Bruss have devised a least-squares approximation technique to handle the special case of pure rotation. An implementation is in progress.

Natural Vision

A model of two important aspects of retinal function has been proposed by Professor Shimon Ullman and Dr. Jacob Richter. Their computational theory addresses the role of the retinal ganglion X- and Y-cells. The X-cells implement in human vision what has been modelled mathematically as the convolution of the Laplacian of a Gaussian filtered image. These cells provide the visual cortex with information about the location of rapid intensity changes, from which intensity features such as edges, bars, and blobs can be detected. The X-cells constitute the basic input for much of later visual processing such as stereo, texture, and contours. The Y-cells, which appear to be the primary input for perceiving visual motion, are modelled as the time derivative of the Laplacian of the Gaussian filtered image. Professor Ullman and Dr. Richter show how these two mathematical functions can be implemented by the neural architecture of the retina, particularly by synaptic interactions.

Dr. Richter has continued this research into the next stage of visual processing, wherein X-cell input to the visual cortex is used to detect the location and orientation of intensity edges. That current line of work dovetails with a theory of edge detection developed by the late Professor David C. Marr in collaboration with Ms. Ellen C. Hildreth.

The processing of retinal intensity information is therefore becoming better understood, and allows the generation of specific computational models for various later processes. In particular, a theory of human stereo has been developed by the late Professor Marr and Professor Tomaso Poggio. A computer implementation by Dr. W. Eric L. Grimson has allowed a quantitative comparison of this model with the known psychophysics of human stereopsis. During the past year, Dr. Grimson also explored several computational issues regarding the process of deriving a representation of a smooth surface given the incomplete sort of information that stereopsis naturally provides.

Other computational problems that are under investigation regard the representation of continuous curves or contours from local edge or line information by Dr. Kent A. Stevens, the detection of texture discontinuities by Mr. Michael D. Riley, and the modelling of directional selectivity to visual motion by Ms. Hildreth.

Finally Dr. H. Keith Nishihara and Mr. Noble G. Larson have developed hardware for processing images with Gaussian filters, thereby working toward a real-time stereopsis machine.

Robotics

Ordinary human abilities, such as the planning of motions in a world of obstacles to reach some goal without collision, are difficult to automate. Professor Lozano-Perez developed a system of wide generality which constructs a hierarchical tesselation of space and efficiently computes grasping positions and paths for a polyhedral object in terms of the space of allowable configurations. Professor Lozano-Perez is now designing a high-level manipulator language in which his spatial reasoning system will be embedded.

In addition to an ability to reason about space, a high-level manipulator language must have an ability to reason about the interaction of manipulators and objects. Mr. Matthew T. Mason has uncovered some simple rules governing the collisions which occur when a manipulator grasps or pushes objects.

Working together, Professor Lozano-Perez and Mr. Mason implemented new software that enables a minicomputer to perform time-critical functions while a LISP-oriented computer does task planning and supervision. This software drives a manipulator designed by Mr. John A. Purbrick, which uses an innovative stepping-motor control system developed by Messrs. Larson, Mason, and Purbrick.

Mr. William M. Silver has worked on another aspect of manipulator control, extending some previous results on manipulator dynamics worked out by Dr. Hollerbach. Dr. Hollerbach had used a Lagrangian approach to obtain an especially simple form of the equations of motion. Mr. Silver demonstrated that Dr. Hollerbach's Lagrangian approach is equivalent to results obtained using a Newton-Euler approach.

A three degree-of-freedom tendon-driven shoulder, designed by Dr. Hollerbach, and two high-resolution touch sensors, one designed by Mr. Purbrick and one designed by Mr. William D. Hillis, continued to receive attention, with emphasis on experiment.

During the past year, a great deal of effort went into preparation for expansion of the Laboratory's work in Robotics. This preparation included the development of ties with other laboratories and centers and with the Department of Electrical Engineering and Computer Science, the Department of Mechanical Engineering, and the Department of Psychology.

Learning from Experience and Natural Language Understanding

Professor Winston's theory of reasoning by analogy has led to a system with the following parts: a hypothesizer that searches memory for precedents likely to be useful in analyzing a new problem; a matcher that finds the most useful correspondence between a retrieved precedent and the given problem using the causal framework found in the precedent; and a reasoning system that reaches conclusions about the problem using the precedent. During the past year, Professor Winston has developed a technique for generating abstract rules as a byproduct of the problem-solving effort. These abstract rules are similar to those that appear in systems developed elsewhere for medical diagnosis and oil-well log analysis. Professor Winston expects his work to lead to learning systems that acquire expert knowledge from experience, reducing the need for expensive and unreliable acquisition from human experts.

Mr. Boris Katz produced an English input module for Professor Winston's analogy system using the same approach he developed for generating English text from semantic representations. His generation system subdivides into three relatively independent steps: the first generates a set of kernel sentences from the semantic representation; the second uses syntactic and thematic considerations to determine the set of transformations to perform on each kernel; the third executes the specified transformations, combines the altered kernels into a sentence, performs a pronominalization process, and produces the appropriate English word string.

Expert Problem-Solving in Programming

Drs. Rich and Waters analyze the logical structure of programs in order to create intelligent programming environments.

They have devised a representation called a *plan*, a language-independent representation for a program that stands above the syntactic details of the programming language and represents control flow and data directly. The central idea is that typical programs are built up in a small number of stereotyped ways by what are called plan-building methods.

The power of the program-analysis system is demonstrated by the fact that it can produce plans for COBOL programs as well as for LISP and FORTRAN programs. Dr. Waters also constructed a coding module which produces LISP code from a plan. It has been tested on several dozen plans, including some which were produced by automatically analyzing COBOL and FORTRAN programs. The LISP programs produced range from several lines to several pages long.

VLSI

Professor Sussman and his associates work on design tools for Very Large Scale Integration (VLSI) and on innovative ways to exploit VLSI hardware.

During the past year, Professor Sussman and Mr. John D. Batali continued to develop the Design Procedure Language (DPL) for describing a hierarchical abstract wiring diagram for a device. Messrs Batali, Edmund Goodhue, and Christopher Hanson have developed software for translating control-unit function into a form accepted by the DPL system.

Dr. Shrobe continued to develop the Daedalus system, a graphics interface to the DPL system. One new feature allows fracture lines to be placed, describing places where a circuit may be stretched. Another allows the conditional interpretation of standard cell parts, allowing proper display even though the use and the precise form of a cell vary.

Mr. Knight has designed and fabricated a prototype silicon image sensor which includes image processing implemented through a hybrid analog/digital approach. The operation of the chip relies on interconnections that make it behave like a finite-element approximation to a distributed transmission line governed by the diffusion equation. The resulting computations are Gaussian convolutions which can be differenced to form approximations to the operations that are required in early vision processing.

Mr. Hillis is currently leading an investigation into the possibility of building a concurrent computing machine for searching data bases with 10,000 times more facts than those in today's expert systems. The proposed machine, called the connection machine, is a locally-connected array of cells. In contrast to the memory cells in ordinary serial machines, each cell in the connection machine is to have not only the hardware necessary to hold an item of data but also the hardware necessary to manipulate it.

Distributed Problem Solving and Computing

Professor Davis studies some of the fundamental issues that must be faced in distributed planning and problem solving. Motivations for distributed planning and problem solving include both economic forces (which suggest connecting many small computers together to work on a common goal), as well as arguments based on reliability and graceful degradation in performance if one of many machines stops functioning. Professor Davis has begun studying planning strategies that make sense in a world populated by multiple agents, none of which has complete knowledge, and is exploring techniques for producing plans that produce robust, cooperative, and cautious behavior.

Professor Hewitt investigates the issues surrounding the creation of multiprocessor systems. A central problem in any multiprocessor system concerns the topology of interconnections between the individual processors, and this in turn determines the lengths of the wires between processors. Some researchers have suggested placing processors at the vertices of an n-dimensional cube so that the maximum number of hops between processors is the logarithm of the number of processors. This topology has the disadvantage that almost all the wires are extremely long, which is disadvantageous in VLSI systems. In order to deal with this problem Professor Hewitt, in collaboration with Professors Robert H. Halstead, Jr. and Richard E. Zippel, developed the idea of using a folded n-dimensional hypertorus, which can be visualized as wrapping opposite sides of the n-cube to make them adjacent. Mr. Jeffrey I. Schiller has constructed a test-bed implementation based on three of the Laboratory's LISP Machines, and a simulator for a 64-node system using the folded Cartesian hypertorus geometry of interconnections. This has enabled pilot studies of the important idea of work sharing and dynamic load balancing to be started. Recently Ms. Phyllis A. Koton constructed a communications VLSI chip called PORTAL-0 to facilitate further experimentation with the Apiary.

The Computing Environment

Several years ago Mr. Greenblatt conceived of the LISP Machine, a computer that gives its users more symbol-manipulation and list-processing power than had ever been available before. During the past year the number of these machines in the Laboratory increased to 14, enabling research that otherwise could not be done. All of the LISP Machines, five PDP10s, two ETHERNET gateways, and miscellaneous computers and terminal concentrators are linked together with an eight-megabit packet-oriented cable system known as the CHAOSNET.

Basic Theory

Professor Minsky continues work on his *society of minds* theory, in which intelligence emerges from the interaction of large societies of rather simple individual agents, in a parallel computational structure. Because each agent is relatively simple, communication between agents must be restricted in amount and in complexity.

Professor Minsky's approach may illuminate the psychological theories of Piaget and Freud, as well as give coherence to Artificial Intelligence theories that do not consider the kinds of problems inherent in the representation of a personality. The limitations of inter-agent communication make it necessary for the mind to develop hierarchies of control structures that may be similar to developmental stages. The censors and critics of the hierarchy settle conflicts by referring to early-developed self-images.

Professor Minsky's work has led to new ways to organize very large knowledge-based computer programs, such as the building of large, active computer memories, useful for dealing with the representation of common-sense knowledge.

Education

The LOGO Group, under the direction of Professor Papert, applies theoretical and technological developments in Computer Science to education. All of the group's activities are done in collaboration with the Division for Study and Research in Education.

Dr. Sylvia Weir, Professor Papert, Mr. Jose Valente, and Mr. Gary Drescher, use computer-based techniques to address the diagnostic and educational needs of children with physical, learning, and emotional handicaps. Work with the learning disabled involves the isolation of a spatially gifted subcategory of the population, using the computer as a source of formal spatial reasoning. This work links recent brain-behavior correlation research with computer-based spatial learning environments that have been generated by the application of Artificial Intelligence to education.

Mr. GORE. Dr. Horn, thank you very much.

Our final witness is Dr. Delbert Tesar, director of the Center for Intelligent Machines and Robotics at the Mechanical Engineering Department of the University of Florida.

Let me welcome you on behalf of the chairman of our full committee, Don Fuqua, who speaks very highly of you and your colleagues there. We are delighted to have you.

Please proceed.

Dr. TESAR. Thank you.

I would like to first describe our center. We have 10 faculty, 25 students, $2.5 million funding over the last 2 years, three-quarter million dollar laboratory. We do have major interactions with industry, and we are keen to maintain a high level of development activity.

I personally have been involved in a position paper development in the areas of innovation, productivity, robotics policy, manpower policy, nuclear reactor maintenance questions over the last 5 to 8 years.

I have traveled essentially in every major institution in the world in the robotics technology under discussion today, including Russia, Europe, Japan, and Australia. So I would like to address the highlights of my formal presentation which has been submitted for the record by means of a few slides.

Realizing of course that I cannot provide an in-depth presentation, I would enjoy doing it at this time. I would like to highlight the fact that I do believe that the robot technology of the next generation does not exist, and there are grave dislocations you might say between need and available feasible technology today.

By means of these slides, I would like to illustrate some of those issues. First we have to be aware of the fact of the magnitude of the problem we are facing. Manufacturing is 24 percent of the GNP and outranks all the other wealth generators in the United States by a large amount.

Mechanical technology represents 75 percent of our manufacturer's trade. Which means it is dominant and we should have policy in proportion to that.

Yet 20 of the most negative deficits in the manufacturing area which are mechanicals produced a $34 billion loss in 1978. This is the same loss we had in oil. We have no aggregate policy or technology to defend that particular issue.

So——

Mr. GORE. Before you move to the next slide, could we get that focused, and let me make certain I understand the slide.

Dr. TESAR. Fine.

Mr. GORE. Where is it?

You have got a total of 36 percent.

Dr. TESAR. That is right. The other 63 percent is service, of which 50 percent is from industry and 13 from government.

Mr. GORE. Now why do you—is service not a wealth generator?

Dr. TESAR. Not in the sense of raising the standard of living. There is a distinction between these four primary wealth generators: agriculture, construction, extraction, and manufacturing versus service industries.

Mr. GORE. Within the manufacturing area, mechanicals represent 75 percent.

Dr. TESAR. That is right.

Mr. GORE. Of our manufacturing trade. What are you calling mechanical?

Dr. TESAR. Those are your big construction equipment, tractors, trucks, automobiles. Any kind of sewing machine or camera, any kind of product, the type that is highly mechanical in nature or the manufacturer of that product.

Textiles, shoes, that sort of thing.

Mr. GORE. Fine, thank you.

Dr. TESAR. Next slide.

If you look at the question of automobiles and aircraft, take that out of the trade and manufacture, you still have 60 percent of your trade in mechanicals. Six percent of the Nation's R&D supports this 60 percent of your trade, so there is a 10 to 1 imbalance.

This crucial element is the issue we are really talking about. Can we put the manpower and resources to meet our needs in this particular competitive environment, especially in the civil sector? If you have a 10 to 1 imbalance, you have a grave difficulty.

In the Federal area, this particular manufacturing sector, you have only 0.7 percent of all the Federal R&D money, which is very large. So there is essentially an imbalance of 100 to 1 relative to this need. So listening to much of the testimony today, this matched up fairly well with the particular reality.

Finally, there is an emerging threat to the civil sector of the United States. Manufacturing R&D will in fact be occurring rapidly with major impetus from the defense sector. That is well and good. But there is a difficulty in the civil sector.

The U.S. manpower is not sufficient to absorb rapidly the results of the defense sector. So that it seems to me foreign civil sectors, specifically Germany and Japan, will be the primary beneficiaries of this technology in the defense sector. We have a coupling there.

Mr. GORE. Again, excuse me for interrupting, but what you are saying there is that because such a heavy percentage of our R&D effort is going to be in the Defense Department over the next several years, it is fair to predict that the civil sector will not be able to absorb that, and, as a result, foreign manufacturers and other parts of foreign civil sectors could be the primary beneficiaries of the R&D in the American defense programs that have commercial application?

Dr. TESAR. That is essentially my argument. I do not know that we can defend that wholeheartedly, but I do believe there is an emerging threat on that particular issue.

Thank you.

[Next slide.]

Mr. SCHEUER. Excuse me. Can you elaborate a little on what those foreign civil sectors are?

Dr. TESAR. For example, in Japan more than half the engineering population is directly involved in civil sector manufacturing. We have far fewer of our engineering population involved directly in manufacturing issues.

Mr. SCHEUER. You mean manufacturing for consumption?

Dr. TESAR. Right, in the civil sectors.

Mr. SCHEUER. Yes. There is a high degree of application of robotics in the manufacture of products for consumption.

Dr. TESAR. Yes, we would hope so. In Russia, I spent several weeks there on a study mission, essentially they have 2,000 to 3,000 robots in use today, their applications in industry are very similar to ours.

But their biggest problem is lack of precision components, cervovalves, encoders, hydraulic actuators, these things we take for granted they have difficulty with. They have plants for robots in Riga; the Cybernetics Institute at Kiev has 5,500 people working only on computers in Kiev, about 50 of those people working on vision for intelligent machines.

Electric Welding Institute in Kiev is one institution of unbelievable stature in the world. It has 7,500 people working only on electric welding—100 of those people are dedicated to electric welding with robots.

We do not have anything like this kind of magnitude in the United States for a true manufacturing process. It is highly dedicated aggregated activity. This kind of activity must not be ignored in our own plant.

Here is an example of a walking robot that has been worked on by the Russians for about 20 years. Steady, consistent sense of direction and funding. This particular technology, although it may look very immature as far as the mechanical device itself is concerned, it is very sophisticated from its control point of view, its equalibrium maintenance, stability for feedback, force level, and so on.

You saw this thing operate over obstacles and be able to sense certain barriers.

Now I say then that without enough background here that our major technological opportunity is more R&D into mechanical manufacturing. It is a key issue here. We do not mean stupid machines which has been stated over and over again today.

Now what we are after is an intelligent machine which combines sensors, process and interpretation and adjustable mechanical structure. This really forces integration of technology that has never been really conceived of in this country, especially at universities.

We have had major disciplines in universities that have been essentially prioritizes, maybe 50, 70 years ago. This kind of integration just does not normally exist in universities. And probably does not normally exist in government and industrial labs, either.

But we are going to have to force all these disciplines to work together to get the kind of technology we mean by robotics. One of the biggest weaknesses by the way is in mechanical structure, though many people involved in robotics today assume the mechanical structure exists, I can tell you since I am a mechanical engineer that this structure that exists today is far inadequate to reach to the next generation.

Here is a modern robot. This is the Cincinnati Milacron Robot, you saw a movie of it this morning. I would like to make one comment about this robot. Certainly it is a modern system which I in fact greatly appreciate. I think on the other hand it is very important to recognize that no single component of technology was created to support this system. In other words, everything that was needed exists on the shelf before this system developed.

So the controller, actuators, encoders, all the components existed. So I think we need to look at both ends of the spectrum, even though universities tend to look at components, I think we need vital technology development in the component area.

The fact is, that is where breakthroughs will come.

Here is a demonstration of a problem I think we are facing in this country, and probably other countries as well. This is a machine made by General Electric. It has a man to control it, a very large essentially robot arm. It is a combination of man-machine.

The point I am tring to make here is that we do not have proper development of man-machine technology in this country. We are now making machines completely autonomous to the great disparity of the need in industry directly. I would like to see a lot more combination of balance between man and machine in real industrial applications.

I might also add putting a man in the loop makes the technology much more demanding. It is much more difficult to have a man and machine working in balance.

Here is an example of a roving coal mine machine designed for the Coal Mine Board in Pittsburgh. It is 25 feet long. The manipulator arm is strong enough to pick up a telephone pole and move it vigorously. It is about 4 years old. A man operates it underneath this canopy. Indicates a concern for hazardous environments in this country.

Here is probably the most integrated of all our robot devices today. This is the Shuttle manipulator that went up 6 months ago. It cost $100 million for this device. The reason I show this slide is to impress on you that new technology, highly integrated technology, bringing the best of your modeling and computer software to bear, is extremely expensive. So this business is an expensive business. Big science involved.

Here is a simplistic application of robotics, but primarily for a hazardous environment like picking up a heavy hot object. The reason I show this slide is to get to the point that I want to next on the next slide, which is that we are using robots for very simple functions today. They do not demand much of the technology.

On the next slide, I will show you what I really would like to have. Here we have a unit process. This process could be electric, arc welding, it could be laser welding with 25 kilowatt level energy. Or it could be working at the circuit level of assembly of small circuits.

Whatever the process is, I want to have immediate connection between the process in real time to the process computer, economic requirements, data and design computer and so on.

What has happened today so far, if you ever have the opportunity, and I really recommend it to everyone, go shake hands with a robot. The first thing you learn is that they all shake. This means that no robot is precise under load. That is where most of the future application is going to be, that really replaces humans. We want precision in process inspection, and we want precision under load.

We cannot get that today. All the applications I am aware of where this has occurred, we also use something like a jig. That jig makes a perfect barrier between the process computer and the process. So that decouples the machine from the computer, which means it will never get to the factory in the future with the present level of technology, except for simple applications.

Now very important to recognize the human system has a whole series of components to make it up. Of course, the robotics system has a whole series. The issue is that we need to work on the component technologies as well as system technologies. Universities tend to do very, very well in this area. We should enhance the universities in this area.

Now this is essentially then what we are after. We are after essentially a machine tree, taking all the developments of the mechanical components and electrical components. These things can be built in the environment of Government and university labs. Then these can be brought up to the application of mission oriented areas, for example, in robotics systems manipulators, adaptive control systems and things like that.

I believe personally that Government labs and industry are much more capable of handling these mission oriented tasks. But the universities tend to do extremely well in the component level tasks. We need to build both of these essentially dual systems up and bring them together in cooperative ventures.

Now at the University of Florida, briefly, human augmentation is our primary target, not human displacement. It can be done in all these areas, for example assembly of complex microsurgery. You can keep the human involved for inspection, decisionmaking or judgment. It is possible to use robots to enhance the surgical motor capacity by at least a factor of 10.

Hostile environments, for example, nuclear reactors. Protheses and orthoses, and man-machine interface. This I believe can be treated only by corporations. It means two robots have to work together in real time, whether human intelligence or computer is not really terribly important.

The problem is that the matchup is a very delicate one and demands the highest level of system development. We do not see enough of this going on this country, and I do not believe the small corporation is capable of doing this at the complete level I would like to see it.

To address the question of scaling of the technology, it is very important to think about robots in scale of relative tasks they are going to perform. Here is a 3-inch robot arm intended for processing microcircuits or microsurgery. It turns out that the Japanese are now rapidly moving toward a small system whereas in this country we have not moved rapidly toward a small system.

We are not scaling our robots to the task. So we have bit robots doing small things. I think we need badly to work into the area of micro robot devices, because there are so many tasks that are very small.

Finally, just a question of the nuclear reactor problem. First, nuclear reactors in this country are down just like all other plants; they are down about 25 percent of the time. But the main issue is 40 percent of the downtime is forced outage. Forced outage is very expensive. So if you look at the next slide with me, by 1990 there will be 150 plants on line, projected cost of just the forced outage, very conservative statement indeed, $2.6 billion per year.

Yet we have no university research in this country right now dedicated to trying to solve this problem. The savings, however, from our study of this particular issue which we spent several years in would be about $1.8 billion per year for 150 plants in 1990.

Just applying this technology to two applications, steam generator and the valves, would save $700 million per year in 1990.

So also, once you have got this kind of technology on board, the applications to other missions become extremely available. In other words, you can now take the technology, remote maintenance for nuclear reactors, apply it to accident missions, coal mine operations, ocean floor operations. There is a tremendous amount of economic benefit associated with ocean floor. These have only to do with engineering. You can go beyond that to other applications where robotics could play a major role.

Now, finally, I would just like to have two slides, one having to do with the proposed national plan to deal with the question of the technology we are having under discussion today. First, priorities have to come from industry. Absolutely crucial that that industry provide priorities. We do need centralized control. We have to have a central agency involved so the thing does not go off in some arbitrary direction.

Cohesive program to treat the problem. And this is the key question. Can we do what MITI is doing? I do not think we have done very well to create a cohesive program.

Finally, I am going to suggest 10 semiautonomous university centers where the university is a key part of the particular partnership—industry negotiated research projects. Industry plays a major role in negotiating the projects.

Now what are the kind of centers I recommend? I recomend about 10 in the areas of light and heavy machinery, manufacturing processes, industrial robots, human augmentation and prothesis, remote robotic systems, artificial intelligence, electro-mechanical, tribology, engineering economics, and human factors.

We are now talking about partnership in industry. A marriage really occurs. It cannot occur if you have weakness. Weakness does not mean we grant you some money and come back a year later. We are actually going to negotiate with you and ask our best people to be involved with you, this sort of thing, you can only do with a major system development of this type.

A cohesive program of that type is what I recommend. I do not think we are going to get it at this time, but I do believe the Japanese and other societies, like the Germans and northern Europeans, are moving rapidly in this direction because they have many institutes representing that kind of technology.

Thank you very much for your time.

[The prepared statement of Dr. Tesar follows:]

Testimony on Hearings for Robotics

Presented to

The Subcommittee on Investigations and Oversights of the
House Committee on Science and Technology

by

Professor D. Tesar, Director
Center for Intelligent Machines and Robotics
University of Florida

I. Introduction

In this brief assessment, the current state of the art of robot systems technology is discussed in terms of applications for industrial automation and remote operations such as nuclear reactor maintenance. The attached appendix reviews the status of the component technologies which must be integrated to create the complex technology now envisioned for present and future robotic systems. Especially, weaknesses are discussed which are reflected in the performance of existing industrial robots which are being used for precision assembly, handling, and component preparation for batch manufacturing type industries (i.e., airframe manufacture, shipbuilding, etc.). The objective of this assessment is to demonstrate the essential need to integrate technologies to enhance existing robotic systems and to move forward as rapidly as possible to the next generation robot system.

II. Economic and Manpower Issues

The author has recently analyzed the competitive position of the United States in value added manufactures. [Ref. 1, 2, 3]. Manufactured goods represent 60% of our trade. Of that trade, 75% is mechanical in nature. Excluding automobiles and aircraft, mechanicals represent 60% of our trade. The portion of our nation's R&D expenditure to support this trade is only 6%. It can, therefore, be concluded that our R&D is 10 to 1 out of balance with this economic reality. Furthermore, only 0.7% of our federal R&D in manufactures (which is almost 50% of our total R&D) goes to enhance technology associated with mechanical manufacturing. Here, the imbalance of national policy is 100 to 1. These imbalances have been at the core of our weakness in the trade of mechanical manufactures. The weakness is perhaps most clearly demonstrated by noting that the 20 worst deficit generators in the mechanical trade categories (automobiles, office machines, cameras, clothing, etc.) created a $34 billion trade loss in 1978, equivalent to our loss in oil for that year. This lack of a cohesive national program also affects our manpower base, especially in engineering.

During the past decade, the United States has produced 5% of its university graduates as engineers, while Japan has produced 15%, central Europe 20%, and the Eastern block, 40%. Also, of the U.S. annual production of 60,000 engineers, approximately 25% are involved in defense related operations. By contrast, the Russian annual production of engineers is 300,000 with 60% involved in defense related functions. This means that there is a numerical imbalance of 12 to 1 in this indicator of technological policy. The manpower priorities in Japan are similarly striking. They have almost 6 times more engineers and scientists per capita than we have and most of them are active in manufacturing industries. Hence, the manpower threat to both our civil and defense sectors appears transparent.

One of the existing and emerging technological fields which may be used as a vehicle to offset these threats is robotics. The two primary pressures which governs present and future applications for robotics is enhanced productivity in manufacturing and reduced hazards to operational personnel in the performance of dangerous tasks.

It is important to realize that 25,000,000 people are now employed in manufacturing in U.S. industries of which more than 10,000,000 are performing manual functions on a semi-repetitive basis. Today, it is estimated that 5,000 robots are operating in the U.S. This represents a penetration of not more than 5 in 10,000 or less than 0.05 percent. Several Japanese manufacturing plants operate today with factors of 5 fewer workers than similar plants in the U.S. Increasingly Japanese plant development is moving towards the manless factory or the factory without lights. Similar advanced factory development is taking place in northern Europe. The technology of intelligent, flexible machines (represented by robotics) is perhaps the central technology involved in these efforts. The opportunity to expand our activity in the field of flexible manufacturing systems (FMS) will require a major cohesive effort by all parties in the U.S. technological community.

Hazardous tasks are exemplified by ocean floor activity and nuclear reactor maintenance (See Section VII). Ocean floor activity is seen to have high economic importance by noting that 19% of the world's crude oil comes from offshore sources [16]. In the U.S. 12.5% comes from offshore of which 3/4 of this was produced on the outer continental shelf. Oil is being produced in 2000 ft of water with drilling depths of 10,000 ft. The future indicates that water depths of 6,000 ft will be reached during the next decade. Costs are high. The Mobil Oil Condeep drilling platform cost $1.3 billion to handle 42 wells as deep as 9300 ft and operates in 500 ft of water. Future systems planned by Exxon will be submerged and operate at 5,000 ft. In this system, a maintenance robot will be required. Remotely controlled vehicles become economical at these depths. For example, at 1000 ft a diver may work for 10 minutes at a total cost of $100,000 while a remotely controlled craft costs $3,500 per day [17]. Todays RCV's are relatively simple but perform the following tasks:

> "inspecting structures, pipelines, and cables; placing and recovering instruments; setting explosives, clearing fouled lines, and surveying under ice."

Hence, robotics as part of the RCV not only results in a dramatic reduction in danger to operational personnel but also becomes a major economic necessity beyond the depth of 1000 ft.

III. Brief History of Robotics Development

During World War II, the processing and handling of nuclear materials became an urgent national objective. It was soon recognized that such materials carried the penalty of damage to human tissue due to radiation exposure. In order to reduce this exposure, shields and long handled tools were developed to perform simple (often delicate), low force level mechanical operations such as the transfer of materials between containers [Ref. 4]. This activity soon expanded to tasks such as the machining of radioactive fuel, the handling and repair of irradiated equipment, and the manipulation of large amounts of radioactive weapons material. Each new task soon demanded considerable resources of men and materials in order to perform the needed remote operations. Not only were skilled technicians being "used up" at an incredible rate (because of ORE restrictions) but whole facilities had to be designed around the highly specialized devices. (Note that the same question and associated consequences have arisen during the 1970's for remote maintenance of nuclear power plants.)

In 1947, the Remote Control Division of the Argonne National Laboratory (ANL) of the Atomic Energy Commission (AEC) was formed to create remote systems technology to meet the need of processing nuclear materials. It began by focusing its expertise and moderate funding on remote manipulator technology appropriate to work in hot cells (see Fig. 1). The first result was the Model 1 manipulator of 1948. Development through 1954 ended in the functionally realiable

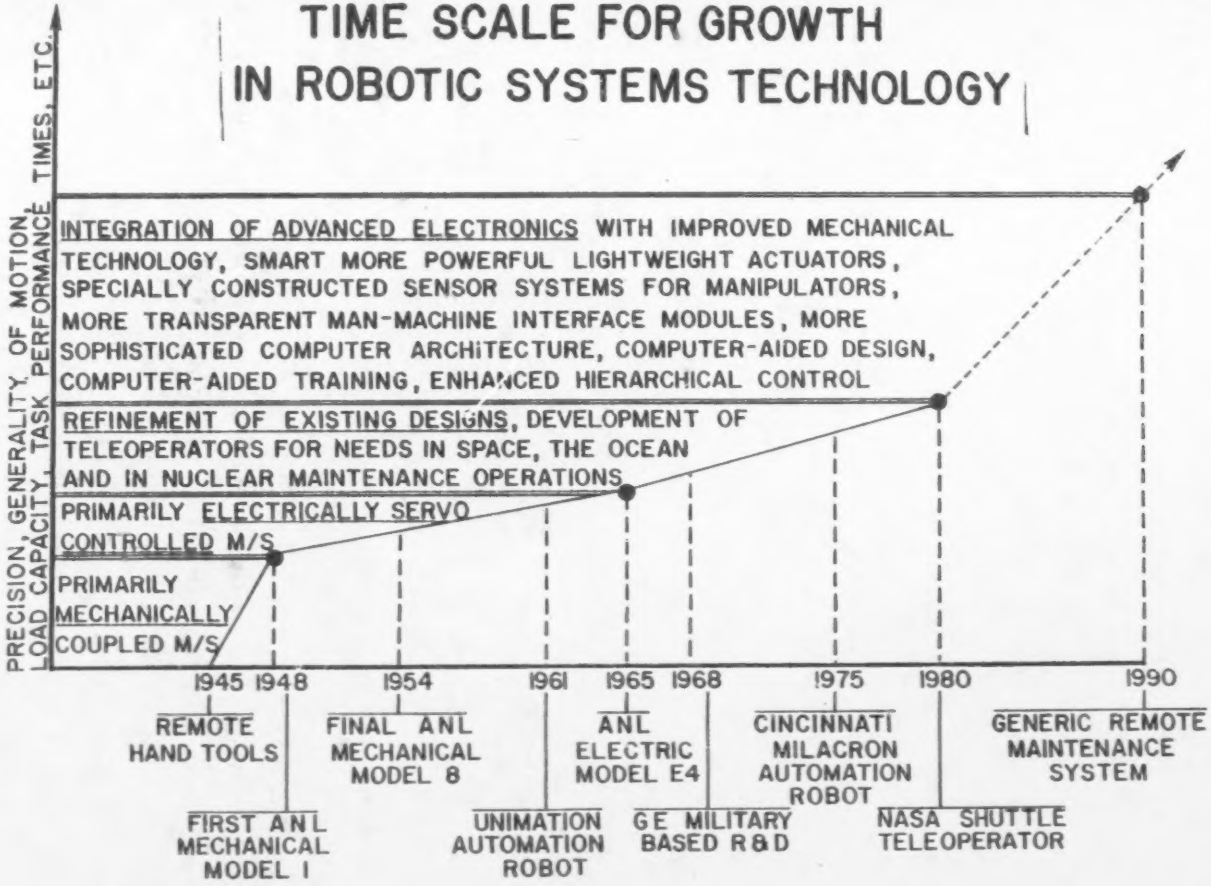

TIME SCALE FOR GROWTH
IN ROBOTIC SYSTEMS TECHNOLOGY
PRECISION, GENERALITY OF MOTION, LOAD CAPACITY, TASK PERFORMANCE TIMES, ETC.
INTEGRATION OF ADVANCED ELECTRONICS WITH IMPROVED MECHANICAL TECHNOLOGY, SMART MORE POWERFUL LIGHTWEIGHT ACTUATORS, SPECIALLY CONSTRUCTED SENSOR SYSTEMS FOR MANIPULATORS, MORE TRANSPARENT MAN-MACHINE INTERFACE MODULES, MORE SOPHISTICATED COMPUTER ARCHITECTURE, COMPUTER-AIDED DESIGN, COMPUTER-AIDED TRAINING, ENHANCED HIERARCHICAL CONTROL
REFINEMENT OF EXISTING DESIGNS, DEVELOPMENT OF TELEOPERATORS FOR NEEDS IN SPACE, THE OCEAN AND IN NUCLEAR MAINTENANCE OPERATIONS
PRIMARILY ELECTRICALLY SERVO CONTROLLED M/S
PRIMARILY MECHANICALLY COUPLED M/S
1945
1948
1954
1961
1965
1968
1975
1980
1990
REMOTE HAND TOOLS
FIRST ANL MECHANICAL MODEL I
FINAL ANL MECHANICAL MODEL 8
UNIMATION AUTOMATION ROBOT
ANL ELECTRIC MODEL E4
GE MILITARY BASED R&D
CINCINNATI MILACRON AUTOMATION ROBOT
NASA SHUTTLE TELEOPERATOR
GENERIC REMOTE MAINTENANCE SYSTEM

FIGURE I

Model 8 which included the very desirable property of force feedback to the operator. The Model 8 was well suited to operations in megacurie radiation fields in which its fully mechanical construction did not degrade. However, it had some significant limitations. The ANL group recognized the importance of these limitations and spent the next decade (1954-1964) developing their initial prototype of an electric master-slave manipulator. The Model E4A servo manipulator overcame many of the limitations of the mechanically coupled Model 8s. In particular, the slave could now be put on a transporter and then moved to a task at some distance from the master. Wheeled and tracked vehicles were being developed by the AEC and NASA [Ref. 5, 6] for remote operations. Also, the power source of the slave was independent of the operator. In 1965, however, the Remote Control Division of ANL was disbanded since the government had decided that the technology had been developed sufficiently to meet the need of hot cell work. This technology was transferred to three other groups who continue to develop it today. These groups are the TeleOperator Systems Corporation, the Central Research Laboratory, and the French AEC.

During the decade 1958-1968, General Electric was involved heavily in electro-hydraulic driven remote systems [Ref. 7, 8]. An early example was the G.E. Handyman installed at Idaho Falls. It had a load capacity of 75 lbs., a nine ft. reach, and adjustable force feedback. It suffered some severe limitations including poor realiability, poor man-machine interface, and a time lag between master and slave of 50 to 150 milli-sec. (a time lag which confuses the operator). It contained some technical sophistication in that it used torque-sensing and transmitting synchros, and compensated electronically for gravity forces acting on the slave. Beyond this development, G.E. worked on exoskeletons (Hardiman) and various walking machines for the military. That effort was terminated in 1968 primarily because the demonstrations failed to satisfy decision makers that further progress could be expected in the near future.

Also, at this time, Unimation put their automation robot on the market and showed that certain hazardous industrial tasks could be dealt with. Much of the early technology by Unimation was due to George Devol [20]. His systems initially employed cam-operated arms, but later applied feedback control technology similar to that used in World War II military hardware. Very little additional development in industrial robotics occurred until Cincinnati Milacron produced their anthropomorphic heavy duty hydraulic T3 manipulator arm in 1975. Perhaps one of the most extensive recent development programs in North America was performed for the NASA shuttle manipulator which is estimated to have cost $100,000,000 over the period of 1975 to 1980. Experience shows that system developments for robotics requires a heavy expenditure of development resources and takes approximately 6 to 7 years to complete. Much of this effort is due to the sparsity of design technology to support the development program for new systems. The complexity of the technology required involves a broad spectrum of technologists and leads to the following conclusion:

> One of the major conclusions derived from this assessment [11] is that the next generation robotic system will require the integration of many technologies which normally have been considered as distinct disciplines. The primary marriage of technologies will be mechanical and electrical. The need to develop component technologies such as sensors and actuators will require an intimate blending of these distinct disciplines. Also, areas such as machine intelligence, human factors, materials, etc. must be integrated fully to create a system capable of satisfying the demands of this unmet technological opportunity.

IV. Recent Interest by National Agencies

Recently, many agencies of the federal government have established mission priorities in the field of robotics as summarized in Table 1 derived primarily from Ref. [18]. This shows that more than $16,450,000 is now being expended annually in robotics related research by the federal government. The program being sponsored under MANTECH at Wright Patterson Air Force Base [19] has documented that precision robotic devices represent a new opportunity to introduce

Table 1. PRESENT GOVERNMENT SPONSORED RESEARCH IN ROBOTICS

	Annual Expenditure
1. In-House Research	
NBS	$1,500,000
NASA	650,000
Naval Ocean Systems Center - Hawaii	300,000
Total	$2,450,000
2. U.S. Government Research Support	
NSF - Production Research	$2,000,000
Mechanical Systems	750,000
Public Technology	450,000
Computer Engineering	300,000
Intelligent Systems	100,000
Total	$3,600,000
DOD - Research	
ONR	$1,700,000
DARPA	300,000
Veteran's Administration	400,000
AFOSR	2,000,000
WPAFB	2,000,000
Total	$6,400,000
DOD - Applications	
Naval Air Rework Facility - San Diego	$3,000,000
WPAFB - ICAM	1,000,000
U.S. Army At	
Aberdeen	?
Ft. Monmouth	?
DARCOM	?
Total	$4,000,000
GRAND TOTAL	$16,450,000

advanced technology (60% of productivity growth) to improve unit processes such as machining and assembly (40% of batch manufacturing costs for the aerospace industries) without jigs for enhanced manufacturing system management (60% of batch manufacturing costs). Specifically, Russo [9] recommends targeting the following component technologies:

Advanced Modeling
In-Process Sensors
Adaptive Learning and Inferential Logic

with the following pay-offs as the primary outcome:

In-Process Quality Control
Performance Optimization (Cost/Quality)
Design Integrated With Manufacturing
Access to New Manufacturing Processes

Hence, there is a general realization that technology must be developed to enhance the performance of present robotic systems in manufacturing and also to move the technology forward to establish the next generation robot technology.

The overall target of the present Air Force MANTECH program and its new initiatives is the factory of the future. This concept was illustrated by Russo [9] in terms of smart, adaptive automated processes (see Figure 2). The whole thrust of this concept is to put the data base in direct communication with (and control of) the unit manufacturing process. This combination of data base with manufacturing could be labeled CAD/CAM and is the major attraction of robotic systems. As mentioned earlier, this application of robotic systems is possible today either for low precision processes or those which are lightly loaded. Where precision and loads are involved, jigs become pervasive and "standard procedure". Since jigs are invariant and very product dependent, they represent a barrier to CAD/CAM or the opportunity envisioned in terms of the factory of the future. One of the important goals of major mission oriented research such as the MANTECH program should be to take steps to reduce the dominance of this barrier to jigs, make CAD/CAM technology a more universal technology, and the factory of the future a near term achievable goal.

V. Present Generation Robot Technology

The robot population [19] is dominated by the Japanese as indicated by the 1981 assessment from the Robot Institute of America:

Japan	14,000
U.S.	4,100
W Germany	2,300
France	1,000
Sweden	600
Britain	500

Most of these robots are used in simple repetitive functions which do not require a high level of sensing, intelligence, or precision. The application spectrum can be illustrated by:

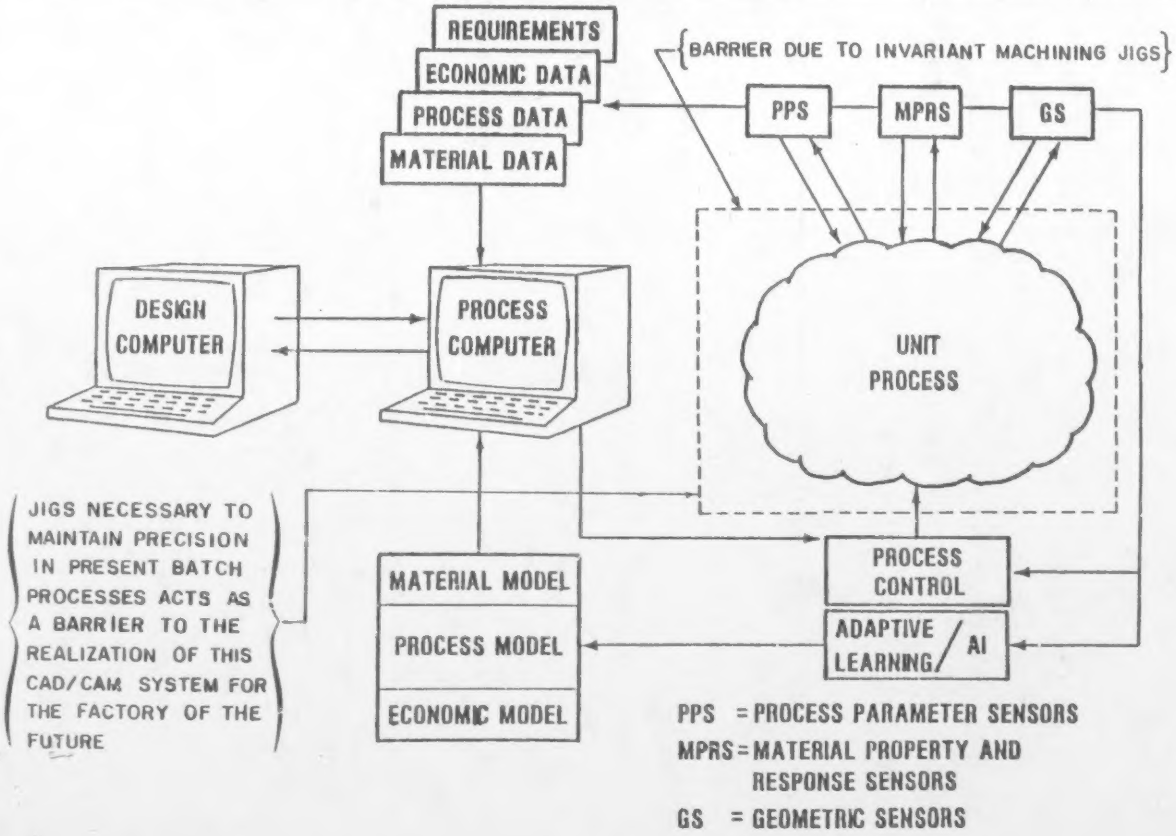
Application	In U.S.	In Japan
Assembly	10%	30%
Loading Machine Tools	20%	40%
Spot Welding	35%	15%
Spray Painting	15%	
Foundry Work	15%	
Other	5%	15%

Most robots being used today do the simplest and most easily achieved industrial functions such as handling of parts from heavy machines (presses), spot welding, painting, and simple assembly. No robot today has the ability to write accurately, to accurately interact with another robot (as do the human arms), to throw or catch an object accurately, to resist significant vibrations (from a grinding wheel), or to perform precision machine operations and assembly. None of the existing systems today are truly adaptive in that they can plan their motion sequence in order to meet a set of constraints, to get around obstacles, to minimize time and energy consumption, or to enhance precision. Even though these existing systems have the perceived dexterity of the human, they fall far short of the human capability and rarely (except in load capacity and endurance) do they exceed it.

The present generation robot is a mechanical manipulator (usually a six axis machine) which is driven by digital commands from a central processor. The only closed loop information available to the processor are position and velocity encoder data at the joints and perhaps either current levels at the electric actuators or pressure levels at the hydraulic actuators. This level of information is insufficient to accurately describe the actual location of the end-effector in space. No suitable technology appears to be forthcoming in the near term to accurately locate the end-effector in spatial coordinates and therefore allow closed loop operation. In fact, almost all robots vibrate at low frequency (from 3 to 10 cps) and when oscillated by means of human "hand shaking" will vibrate with amplitudes of 3/8 to 1/2". This means that no robot arm is truly accurate under load. If robot arms are not accurate under load they cannot be expected to do precision machining operations, make precision measurements during such operations (automatic inspection), nor respond to an independent set of commands from a CAD/CAM data-base.

Today, state-of-the-art requires that jigs be used to support the manipulator structure while a precision machining task is being accomplished. A major airframe manufacturer developed a precision jig to guide the drill bit held by a robot while drilling hundreds of holes in a composite wing surface. The jig cost almost ten times the cost of the robot and required a complex and daily calibration. The robot system merely automated the sequencing of the hole-to-hole drilling procedure and then preloaded the drill so that cutting action was ensured. It made no contribution to the precision hole location layout nor to its inspection. This jig is essentially a barrier to flexible

FIGURE 2 : **SMART, ADAPTIVE AUTOMATED PROCESSES**


REQUIREMENTS
ECONOMIC DATA
PROCESS DATA
MATERIAL DATA
BARRIER DUE TO INVARIANT MACHINING JIGS
PPS
MPRS
GS
DESIGN COMPUTER
PROCESS COMPUTER
UNIT PROCESS
MATERIAL MODEL
PROCESS MODEL
ECONOMIC MODEL
PROCESS CONTROL
ADAPTIVE LEARNING / AI

JIGS NECESSARY TO MAINTAIN PRECISION IN PRESENT BATCH PROCESSES ACTS AS A BARRIER TO THE REALIZATION OF THIS CAD/CAM SYSTEM FOR THE FACTORY OF THE FUTURE

PPS = PROCESS PARAMETER SENSORS
MPRS = MATERIAL PROPERTY AND RESPONSE SENSORS
GS = GEOMETRIC SENSORS

automation in that its form is necessarily static. Because of its invariant form, the jig prevents any response to an arbitrary CAD/CAM data base, the goal of the factory of the future.

A second example of today's state-of-the-art involved the precision routing of air frame surface panels that must be cut to ±1/16" to ±1/32" accuracy. These panels must have a large variety of 3 dimensional shapes. They are pre-cut oversize and formed in a press. Then they must be cut to final specification with a high speed router cutter. Today, this is accomplished by placing the uncut panel in a jig which has precision surfaces on which concentric (with the router cutter) rollers can roll. Hence, again the robot only provides the preloading and sequencing of the motion of the precision cutter. It is not responsible for any of the accuracy requirements either during the process or during inspection.

Grumman Aerospace faced the problem of drilling in spatial wing surfaces 5 years ago. They built a special large X-Y-Z table with a drilling head. This machine provides the desired level of accuracy and it can respond to a broad range of input commands. This technology does represent a solution but it does not lead us towards a "generic" technology or to the next generation robot. A very recent report [Ref. 10] on industrial robot usage and development outlines in great detail the application spectrum and the on-going research in robotics in the United States. It represents an excellent summary of the characteristics and limitations of the present generation of robots. One of their key recommendations is the following for improved positioning accuracy:

> Robots can achieve positioning accuracies on the order of ±010, ±020, ±030 inches. However, many assembly and machining operations require accuracies of less than ±.005 inches. The only way to assure a high degree of positioning accuracy with current robots is to manually teach them. In assembly or machining operations requiring a high degree of accuracy, off-line programming cannot be used. This means that robots will not be economical in batch or job shop assembly or

machining operations because of the high programming cost incurred in manual teaching. The only way to improve accuracy is through some form of robot calibration technique, or through greater precision in the manufacture of robots.

VI. The Next Generation Robot System

It is extremely important to realize that the human system performs its function because of unsurpassed hand-eye coordination. Nonetheless, the human system is probably a very poor model for performing precision operations under load. This fact has not been widely recognized and to a great extent slows the scientific community's response to this valid need. Note that no human hand is capable of precision measurement or is capable of precision machining operations under load. Because this is true, the human model for robotic manipulators is adequate for simple repetitive tasks such as:

Pick-and-Place
Spot Welding
Spray Painting
Surveillance
Unloaded Assembly
etc.

A precision system capable of high loads in real-time operation could perform such tasks as:

Precision machining without jigs
Precision inspection during operation
Multi-level operations under CAD/CAM control
Force fit assembly
etc.

In addition to these immediate process requirements, the following issues must be addressed in the next generation robot system:

i. Accuracy diminishes with time because of drift. Drift is caused by temperature variations, and variations in input parameters associated with prime movers and the control circuit. For example, the properties of hydraulic fluids are very temperature sensitive. Electric motor characteristics also change with temperature. Ambient hydraulic pressure or voltage to the prime movers may change. In other words, the robot needs to be continuously updated in order to maintain accuracy over long operational periods. The robot system must be self-calibrating in real-time.

ii. A workable robotic system should be capable of operational self-improvement on the basis of experience of operation (i.e., self-adaptation in the control circuit). Specifically, certain control parameters can be adjusted to minimize the system's sensitivity to parameters in the robot system or parameters in the operation being performed by the robot. Much could be accomplished by making a statistical analysis of the system's response to a broad range of system or operational variables.

iii. To date, robots used in precision assembly are capable of only light loads and performing only under conditions which are repetitive and unchanging. One contradiction is that high load actuators provide very poor resolution and vice versa, high resolution actuators provide very low load capacity. This fundamental contradiction appears to be unsolvable in terms of the present state-of-the-art.

Most manipulator arms are accurate to about 0.050 inch which is insufficient for many precision operations such as assembly operations and spatial motion functions (for example, laser cutting and welding operations). Precision requirements will intensify as robotic systems become smaller (micro-robotics) and are applied to such functions as micro-surgery. Generally, deformations under small applied loads in existing commercial systems substantially exceed the static (or repetitive) precision level they can achieve. In addition, the operating environment (temperature, loads, shocks, vibrations, etc.) cannot always be considered invariant. Hence, future robotic systems must be much more adaptable to "control-in-the-small" and real-time modeling to meet this second higher level of precision to be developed in the next generation of robot.

In addition, a pervasive constraint on the application of robotics in manufacturing has been that they must be autonomous (operate without human intervention). In order to penetrate the market of manufacturing in the near term, it will be essential to use a combined human-robot system in many cases. Robots will be able to maintain high precision, to work in hazardous conditions, to carry out tasks clearly impossible for the human, etc. Humans, however, have the proven capabilities of inspection, decision making, and judgement. Obviously, our goal must be to improve the robotic system's "human" capabilities. Yet, many of these attractive characteristics are years away. It is argued here that today, the best solution is to use a balance of human and machine capabilities in many industrial applications. As the machine technology improves, less will be asked of the human and more will be asked of the machine. This philosophy allows maximum penetration of the manufacturing market with existing technology, a gradual and natural transference to more machine oriented systems, and a minimum of disruption of the manufacturing workforce.

As a consequence, it is realized that the autonomous machine is the goal but the robotics community must be realistic enough to accept the present limitations of the technology. The recommendation is to work on all aspects of the machine system in order to make it apply to the broadest possible range of industrial applications. In order to reach this breadth of application, the required research must center on the system itself, where precision of operation, dexterity, sensors, real time operation, interface with human operators, adaptive control, etc., are significant technological areas of activity.

The human scale of operation in manufacturing is an immediate goal. However, many operations (for example, high intensity continuous path laser welding) either greatly exceed human capabilities or are completely impossible by direct human involvement. Hence, many unknown demands on the future robotics system must be considered at this time in research programs in the United States.

Existing robotic systems are superior to those of a decade ago. The goal should be to not only expand the capabilities of existing robotic systems (better sensing, more precise actuator control, compensation for dynamic loads, etc.), it should also be able to develop the technology for the next generation robotic system aggregating the best of the advanced technologies of sensing, microprocessors, precision encoders, computer architecture, etc. to achieve an integration far superior to that now extant.

VII. Application to Remote Operations

One of the most pressing remote functions suitable for robotic systems application is maintenance of nuclear reactors. Near term technology represented by this emerging field could dramatically reduce man-rem exposure (or other hazardous exposure) to maintenance personnel by reducing or eliminating "hands on" operation. In many applications, significant economic benefit could be derived by reducing down-time of the energy system - especially for nuclear power plants. The cost to the nation in 1980 is not less than 1 billion dollars per year for forced outages of existing fission plants alone. Remote maintenance technology has been argued to save $700,000,000 of this loss (Ref. 11). These numbers would increase by a factor of 2.5 in current dollars by 1990.

The primary use of manipulators in remote operations today is in hot-cells. These operations are well defined and the tasks are predetermined. Unfortunately, the maintenance task for nuclear systems is usually poorly structured. Hence, the operator must govern the system by visual and force feedback in order to function in this unstructured environment. Successful remote maintenance will require manipulators and transporters which can obtain access to work scenes (including numerous obstacles) presently accessible only to man. The recent assessment (Ref. 11) argues that the current level of technological development is insufficient to accomplish these demanding and complex tasks in a reasonable time (or at all) with today's remote systems technology. Two component technologies are particularly weak; i.e., the manipulator geometry (high dexterity and obstacle avoidance) and the man-machine interface (the quality of the coupling between the operator and the remote system so that speed and precision is assured). The conclusions are:

> The best of current manipulators, the bilateral master-slaves, cannot do all of the tasks demanded of them in the unstructured environments of nuclear reactor maintenance. New and innovative teleoperator systems with high levels of manipulator dexterity must be employed. This will necessitate the design of a highly transparent man-machine, computer controlled interface for effective manipulator control. Principal concerns for the operation of future remote maintenance systems center on precision, load capacity, and overall task accomplishment times. Precision implies that there is a high resolution of the system's motion (a factor of 10 better than present systems). Load capacity improvement would suggest a significant advance in actuator development. Finally, present systems operate at 7 to 20 times the time necessary to accomplish a given task with the human acting alone. Reduced task times will mean reduced outage costs and reduced operator radiation exposure and will be necessary to make remote system technology competitive economically.

The above conclusions indicate that speed and precision are important considerations for the operation of a remote maintenance system. The operator remains as the focus of the intelligence of such a system since as many as 25 distinct operations must be performed sequentially in an unstructured task environment. This highlights the following recommendation for development of a viable man-machine interface technology:

> The man-machine interface should be developed so that the human operator can experience the best possible interface for all his sensory receivers and his motor and speech outputs. Then the interface will approach the desired level of transparency. The more generalized manipulator structure cannot be controlled effectively by a human operator by using a geometrically equivalent master controller. The necessary machine software and hardware, capable of decoupling the geometry of the input (controller) and the output (manipulator), should be developed. This means the development of transparent universal manual control interfaces (hardware) and the associated computer programs (software) to command a given family of manipulators.

A major workshop [Ref. 12] on remote systems technology was held at the University of Florida on March 9, 10, 1981 to evaluate means to develop the required technology for remote operations. In addition to nuclear reactor maintenance, several other applications were presented as potential beneficiaries of this needed technology. These were:

1. Accident Missions
2. Coal Mining Operations
3. Ocean Floor Oil and Mineral Operations
4. Remote Operations in Space
5. Arctic Exploration and Field Operations
6. Energy Test Facilities (Fusion)
7. Nuclear Fuel Processing
8. Maintenance of High Voltage Transmission Lines
9. Decommission of Nuclear Facilities
10. Operations Following Major Unplanned Events Such as TMI.

VIII. Robotics Development in Other Countries

Recently, the United States has become painfully aware that it is not leading the applications race to put robots to work for enhanced productivity. Japan presently builds 45% of the world's robots (about 3 times more than the U.S. does) and is initiating a major national plan to spend $140 million over a 7-year period to develop new intelligent robots capable of assembling all kinds of products [13]. Essentially, it appears that Japan's overall development and implementation effort is ten times higher than ours relative to the associated national GNP's. A quote from Aron [14] shows the level of commitment in explicit terms:

> "The Japanese consider robots crucial to the continued growth of their economy. The electronic workers are a key element in flexible manufacturing systems (FMS), viewed as the most economical method of manufacturing in an era of

> of shrinking production runs and shorter product life cycles. Companies are seeking alternatives to today's fixed-automation lines because the capital costs involved in changeovers are more and more difficult to justify. With robotized FMS lines, changing the computer software will usually do the trick.
>
> "Last spring Hitachi Ltd. formed a 500-man technical task force to develop a universal assembly robot with both visual and tactile sensors. By 1985 the company hopes to use such units for 60% of its assembly operations. Similarly, Matsushita Electric Industrial Co. has mobilized its technical staff to refine the modular, building-block robots already in limited use. These robots are grouped to perform such operations as assembly followed by quality inspection. Nippon Electric Co. has developed an assembly robot that can position a component with inhuman accuracy, with a maximum error of 4/100,000th of an inch. And Fujitsu Fanuc Inc. recently unveiled a robot that is even more precise and can recognize and sort parts before assembling them."

The estimated market for Japanese robots in 1985 is given unofficially as $2.2 billion and $4.5 billion in 1990, approximately 4 times the market value expected for U.S. robotic systems. These numbers apply only to the generic, intelligent robotic manipulator system classed as a robot in the U.S.

The Japanese Industrial Robot Association (JIRA) recently published a report that robots had a great role to play outside of manufacturing in such fields as hospitals, agriculture, service industries, and dangerous primary industries such as mining [21]. JIRA forecast that the Japanese market for robots outside manufacturing in 1985 would reach $27 million and approach $360 million by 1990.

The Russians are also vitally interested in robotics development [15]. Russia has recently established a national plan to develop robotics for industrial applications. About 2 to 3 thousand robots are now being used in watch assembly, spot welding for autos, hazardous industrial tasks, nuclear fuel processing, electric arc welding, etc. Their major barrier to rapid progress is their lack of precision components such as servo-valves, encoders, hydraulic and electric actuators, sensors, etc. Several of their research institutes have 100 individuals working on robotics. They are building a plant for robotics in Riga. Russia wishes to match U.S. production of robots by 1985. Overall, their technology appears to be 10 years behind ours at this time.

Generally the most extensive and advanced research in Russia takes place in their Academy of Sciences Research Institutes which pursue base technology, simulation and design, experimentation, and prototype demonstration. High priorities for robot welding cell development have been established in Kiev. There appears to be an extensive history for artificial intelligence and mathematical linguistics at Leningrad. A 20 year research program has yielded a high quality locomotion system with 6 legs, coordinated motion, and balanced force feedback. At Kiev, a mission directed vision project to analyze quadratic surfaces (90% of man-made objects) in real time is well established mathematically and being demonstrated in the laboratory. Finally, the Machine Sciences Institute of Moscow is studying link structure, composites, real time digital position control, and experimental analysis of dynamic phenomena including vibrations.

Some indication of the Russian development program can be obtained from the tabulation of active robotics research groups given in Table 2.

Of course, many of our trading partners in Western Europe are developing robotic systems, particularly Sweden, Germany, Italy, and France. The French are investing $50,000,000 on a program to develop automation robots, primarily for the automobile industry. Mr. J. Vertut is director of a group at CEA, Saclay, near Paris. He is one of the pioneering designers of robotic systems. He has been working on robotic systems for remote maintenance in nuclear systems for 25 years. Today they have extensive cooperation with the robot manufacturer, La Calhene, which has produced 850 systems.

TABLE 2: Russian Institutes Working in Robotics

Institute	Total Staff	Robotics Staff	Research Topics in Robotics
Moscow			
Machine Sciences Institute	1,300	100	Robotics mechanical design, real-time control, dynamic experimentation (vibrations, etc.)
Problems of mechanics	-	8	High level theoretical work in gyroscopes, automatic control, system dynamics.
State University Institute for Mechanics	-	20	Walking machines, real-time analog-digital control.
Leningrad			
Railway Institute	1,400	-	One of 15 railway institutes. 13,000 students, 800 faculty, 600 researchers.
Polytechnic	-	100	Training program for industry, implementation of robots in industry, miniature robot for circuit boards.
University of Leningrad	-	-	Application of artificial intelligence in robots.
Riga			
Polytechnic	-	20	Includes factory for robots in Riga, design of small robots, 13,000 students.
Tallinn			
Cybernetics Institute	460	5	Automatic control, automation, data banks
Kiev			
Cybernetics Institute	5,500 (2,000)	50	Vision of quadric surfaces, machine intelligence, self-calibration, real-time adaptive stacking algorithm.
Electric Welding Institute	7,500 (2,000)	100	Major program in welding & welded structures (T-34 WWII tank armor) implemented own robot design--cooperation on major robot-welding cell with other socialist countries, major effort in sensors for welding.

In Germany, the University of Aachen has an institute for machine technology and manufacturing. It is staffed by 750 people and treats a broad range of short term and long term research heavily funded by the German government and guided by strong industrial priorities.

The Institute fuer Produktionstechnik und Automatisierung (IPA) of Stuttgart is another automation laboratory of 100 people with 25 involved in robotics development. They have completely tested and documented the operational properties of 30 robots. They work primarily on sensors and robot applications for such tasks as welding and assembly. Their yearly budget for the institute was $8,000,000 in 1980. They say that there were 1250 working robots in Germany at the end of 1980.

Overall some of the most precise robots (robust and lightweight) have come from Western Europe. These are represented by the German Kuka and Schlatter, the Swedish Asea, the Italian Sigma, and the French Cyro. Generally, the Europeans have found it possible to establish strong partnerships between industry and academia. This has borne fruit in the emerging field of robotics.

IX. Recommendations

The application of robotics is closely related to mechanical processes in manufacturing of man-mandated products. Because robotics forces the integration of numerous technologies that frequently have remained separate, it may very well act as a catalyst to the resurgence of our productive capacity. In this regard the following general recommendations can be made:

i. A cohesive and structured national program for mechanical technology and manufacturing be established.

ii. A major ingredient is that ten centers attached to geographically distributed universities be formed as the focus of the following technologies:

    1. Light Machinery
    2. Heavy Machinery
    3. Manufacturing Processes

4. Industrial Robots
5. Human Augmentation and Prostheses
6. Remote Robotic Systems
7. Artificial Intelligence
8. Electro-Mechanical Components for Intelligent Machines
9. Tribology
10. Engineering Economic and Human Factors

iii. Another major ingredient is the heavy participation of industrial governing boards to guide the missions of each of these centers for the appropriate class of technology.

iv. There must be heavy involvement by the federal agencies, initially, perhaps with as much as 75% of the funding. This funding would reduce to a residual level of 25% to maintain a centralized control and oversight function.

v. The state or local region should provide land, buildings, and a constant level of 25% funding because the geographical region would be an immediate and continuing beneficiary.

vi. After a period of operation (perhaps 5 years and not more than 10 years), the center would be required to bring in 50% of its funding by direct negotiation with interested industrial parties and groups of industries seeking solutions of real technological problems.

vii. The educational role of the centers would be substantial in keeping practicing engineers ans scientists abreast of the latest developments in the mission area no matter where these developments occurred in the world.

viii. Each center would have specially trained management intimately aware of needs by participating industries of the mission area. This intimate awareness is essential to enhance the required negotiations in the formulation of the assistance plan, in the performance of the task, and in the assessment of the results for further distribution.

ix. It is necessary that each of these centers represent a critical mass of principals capable of meeting the most advanced needs of industry. It is suggested that 50 principals and 100 support personnel would be warranted for 4 to 5 of the centers and about half that for the others.

x. The prestige, effectiveness, and focus of these centers will be enhanced by a meaningful financial base. Hence, a total program of $100 million/year is recommended. This represents only 1% of our yearly loss in light machinery and its products alone. To do less is not to face the problem which is an increasing deficit already exceeding $35 billion/year and potentially much greater.

- Since Technology represents about 40% of our productivity base, concerted activity at this time is essential to prevent a further worsening of our technology gap. No action now will result in a much greater tax on our people which during the last decade cost them an effective reduction of their individual take home pay of 20%.
- Not solving this problem means that more jobs will be shipped out of the country, clean light industry will be built in other countries, and the corrective pressures on our technological institutions to take compensating measures will decrease.

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APPENDIX: STATUS AND DEVELOPMENT OF COMPONENT TECHNOLOGIES

A large number of component technologies affect the development of the system technologies necessary to perform remote maintenance functions and industrial automation. The primary component technology which is making revolutionary development possible is micro-electronics. In addition, components such as vision, sensors, prime movers, control hardware, actuator modules, and end-effectors all support further development of the system hardware. The role of each of these technologies will be briefly described in this section of the assessment.

1. Micro-electronics. Since 1965, the growth of the field of micro-electronics has been phenomenal (Ref. 1), and is the primary reason that accelerated development in robotic systems technology becomes feasible now. Its application to all aspects of the system is pervasive. The goal is the distribution of micro-electronics throughout the system (distributed intelligence) in order to make smart sensors, smart actuators, etc. The growth of the technology of micro-electronics can be summarized as follows:

- Speed of operation up by ten times since 1972
- Cost in 1980 down to 1/6 of 1977 cost
- Density doubling every two years
- Reliability enhanced by multiple circuit redundancies
- Distributed intelligence in machines is a major technological opportunity

2. Vision and Sensors. Relative to the role of sensors in biological systems, sensors are used only superficially in robotic systems today. Sensing may be performed to create information for use by both the machine intelligence (computer software) and the human intelligence (operator) of the total system.

Accurate position encoders can quantify the relative position of manipulator joints with an accuracy of up to 18 bits. This information allows the central processing unit to evaluate the global position of the manipulator. For human intelligence, the primary sensors are that of vision (remote TV viewing) and force (force feedback to the operator's hand). Normally, the signals to the human operator remain in the form of analog signals except that these analog signals may be enhanced by machine intelligence.

Experience has shown (Ref. 2) that more than 1000 lines of resolution in the TV screen can not be utilized by the human eye. New vidicon cameras are now available in a size of 2/3 inch with 600 lines and an intensity of 5 lux (Ref. 3). New solid state cameras are becoming the equal of vidicon technology (Ref. 4). Even so, vision quantification and enhancement is infrequently being used in remote maintenance and automation operations (Ref. 5). One of the primary reasons is that scene quantification of visual shape data is very time consuming for computational hardware (Ref. 6). Experimentation (Ref. 7) shows that the best overall approach to vision is to use light shadows with 2 dimensional black and white TV images.

Non-imaging sensors include touching, grasping, force, and ultrasonic proximity devices (Ref. 8, 9, 10, 11, 12). All of these sensors can be used to send gross information to the machine intelligence or to the human operator about the operation of the system. The proximity device is most useful in obstacle avoidance. Tactile, grasping, and slip sensors attempt to duplicate the sensing role available in the human hand. Thus far this technology has been tested in the laboratory and found to be only modestly useful.

The most useful non-imaging sensor is the force sensor built into the end-effector of the manipulator arm (Ref. 13). This device is able to detect a general force and moment of 3 dimensional space. Unfortunately, it can not locate the force uniquely in space and it requires a sizable amount of computational effort and time. The objective is to integrate micro-electronic chip technology at the sensor in order to make this computation in real time. This development of a smart force sensor is seen to be essential in the near term.

Another potentially useful sensor that has been developed recently (Ref. 14) is the ring laser gyro. It establishes an inertial reference in space without being dependent on the limitations of the manipulator arm structure. The ring laser gyro is vibration insensitive, precise, miniaturized, and reliable.

The primary dilemma for sensing to date is that accurate data on the condition (spatial location) of the end-effector (and the rest of the arm as well) without using sensors attached to the arm structure (which introduces errors and great complexity) remains essentially impossible today. Hence, the human must frequently remain in the control loop to take advantage of visual feedback of the position of the end-effector (which is accomplished without the use of the structure). Near term activity will develop sensors capable of accurately quantifying the arm's operation and making the role of the computer software more effective.

3. Prime Movers. The muscles or energy sources which move the manipulator arm are the prime movers of the system. These components may be electric, hydraulic, or pneumatic. Electric prime movers are the most common. Because of their inherently low load capacity, they always need mechanical force amplifiers in the form of gear trains and metal tapes. These amplifiers all add weight, compliance, and backlash, and they increase maintenance and reduce reliability. A common example is the digital stepping motor (Ref. 15). The D.C. motor produces

5 times the torque of the A.C. motor (Ref. 16). The rare earth metals in rotors of pancake motors now being offered hold the promise of being lightweight and of high torque capacity.

Hydraulic prime movers (both linear and rotary) have the major attribute of high load capacity. Some of their associated limitations are that there must be a sizable high pressure pump, the actuators leak under high pressure (critical in some clean room operations), are sensitive to dirt in the fluid, and special fluids must be used in radiation environments (Ref. 17). Another aspect of fluidic actuators is the delicate operation of servo valves whose design is still essentially a "black art" (Ref. 18, 19). To evaluate the actuator's performance, the bulk modulus of the fluid, the inertia of the fluid, non-linear fluid flow, stiction and friction must all be considered (Ref. 20).

By contrast, the pneumatic prime mover has no leakage problem since the fluid in an inert gas. It is capable of high speed, high force, and low weight. Its primary weakness is its low stiffness, making arms driven by pneumatics very deformable under load (Ref. 21). A comparative analysis between electrical and pneumatic prime movers is given in terms of weights, torques, power, and efficiences in Ref. (22).

Overall, an increased level of sensors and local machine intelligence can make prime movers smart and improve their performance (Ref. 23). This local decision capability would make each prime mover a module in its own right and therefore much more easily assembled into a total manipulator design.

4. Actuator Modules. The combination of the prime mover and the joint structure can be called the actuator module. The first priority for the joint is to eliminate backlash and compliance. Beyond that the range of motion should be as large as possible to enhance the system's reach, operational volume, dexterity, and obstacle avoidance. The elbow of the representative manipulator

arm SM-229 (Ref. 24) rotates 180 degrees. Even though the control tapes to the joints are very compliant, they are used because they reduce the mass content of the movable portion of the arm dramatically (Ref. 25).

Linear hydraulic actuators provide high load capacities and are frequently combined with rotary joints. These combinations however, have a small motion range (110 degrees). The Florida Elbow combines opposing linear actuators with linkage amplifiers to obtain a 220 degree range of motion and the elimination of backlash (Ref. 26). Rotary vane hydraulic actuators are very compact but they exhibit a higher level of compliance than do linear actuators. The General Electric linear actuator-rotary gear and rack provides a large rotation but allows some backlash (Ref. 27). Finally, the Martin Marietta electric pancake motor is combined with opposing gear trains to create an actuator of exceptionally high resolution (Ref. 28). Unfortunately, it has a low load to weight ratio. In general, linear joints are not used widely in robotic systems since they are heavy, less precise, and exposed to dirt.

Considering the nature of the human system, it is noted that few human joints exhibit a single degree of freedom movement. The shoulder has 3 DOF, the ankle has 2 DOF, the wrist and forearm have 3 DOF, and the hip has 3 DOF. Such configurations offer compactness, simplicity of arm geometry, and ease of control. The princial problem is the integration of the prime movers into the multi degree-of-freedom geometry in order to make it move with precision and high load capacity. The University of Florida (Ref. 26) has created a 2 DOF "knuckle" and 3 DOF "shoulder" for this purpose (in addition to the elbow mentioned earlier). The objective is to create joint modules with a full range of sizes which are completely documented for application by the designer as an off-the-shelf item. On this basis, it would be possible to choose these modules and quickly assemble them into a general or special purpose robotic manipulator almost with the same ease as gear pairs are now specified by machine designers. It must be kept in mind that these modules offer structural simplicity but they may reduce the generality of the motion possible.

5. End-Effectors. End-effectors are the tools that are attached to the end of the manipulator arm to perform specialized functions such as welding, drilling, locking or unlocking bolt assemblies, etc. This type of end-effector is quite common in remote operations in nuclear systems. They are necessary because present day manipulators are not sufficiently capable of precision functions under high loads. Some end-effectors are multi-purpose devices in the same sense that the human hand is able to hold a hammer, screwdriver, or other hand tool. On the other end of the spectrum are air driven impact wrenches designed specifically to tighten or untighten bolts. Frequently, tools must be interchanged, a process which must be time efficient and very reliable since a dropped tool could be very difficult to retrieve.

The complexity or specialization of the terminal device is an inverse function of the complexity of the arm, i.e.:

i. general purpose terminal devices require high dexterity, complex manipulators.

ii. special purpose terminal devices can be used with simple manipulator geometries.

The second combination is the one first pursued in the development of a remote maintenance and automation system (Ref. 29). As the technology matures, the first combination becomes more feasible.

6. Control Technology. The first attempt to couple a master and a slave by means of a control computer occured at ANL in 1962 (Ref. 30). The first experiments to control the position and path of the terminal device by means of a digital computer were performed at MIT in 1967 (Ref. 31). A later study

(Ref. 32) showed that a computer would never match the human brain, especially for hierarchical decision making. Since in the near term (< 10 years), it is unlikely that a robot will be "taught" to do a variety of tasks with sufficient adaptability (as in the unstructured task environment on the nuclear reactor), the human must continue to be the primary part of the command and control system (Ref. 33). Because maintenance operations involve a series of discrete tasks, the goal is to reduce the burden on the operator so that he can truly act as a supervisor over the system. For example, obstacles can be avoided by using low level proximity sensors in combination with special computer software (Ref. 34, 35). The mathematical description of obstacles is an incomplete technology at this time, however. The ability of a remote system to learn based on its experience and act accordingly (adaptive learning) is one of the most esoteric of all technologies; i.e., a system which would essentially establish its own software. Teaching the system repetitive tasks by means of input commands from the human operator is achievable technology today. This teach-and-repeat capability leads to a form of supervisory control by the human operator (Ref. 36). Digital control technology represents the best near-term opportunity to integrate the multiple layers of information and decision making necessary to control a maintenance type robot. Work on this important topic (Ref. 37, 38) is being pursued primarily in laboratory demonstrations.

Throughout this assessment, it has been argued that digital signals from a machine intelligence must be used to command the arm motion. This means that the 6 coordinates for the motion of the "hand" (or end-effectors) must be transformed into the 6 (or more) joint parameters of the manipulator arm. This transformation is one of the most demanding mathematical tasks facing the researcher and designer (Ref. 39). The first level of this solution is an algebraic polynomial which may be up to the 32nd order. The solution to this polynomial allows the solution for the arm motion to be obtained without major computational iteration. Fortunately, a very large class of manipulators are controlled by a quartic polynomial which can be solved efficiently in closed form. Hence, the design and optimization of all quartic arms is a first priority.

Beyond the determination of the motion laws for manipulators, there is the design task of determining the link dimensions of the arm itself (Ref. 40). The objective is to choose dimensions which enable the arm to satisfy a specified motion capability. Another design task is to predict the velocities, accelerations, and inertial forces in the system (Ref. 41, 42, 43). The design task treated most incompletely is analytical determination of the natural frequency of the arm due to its mass and compliance content (Ref. 44, 45, 46). The natural frequency is a basic indicator of the quality of operation of the system. Most arms have natural frequencies below 300 cycles per minute which means that they can not be operated more rapidly than 6 cycles per minute in order to minimize vibrational oscillations.

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Mr. **Gore**. What is tribology?

Dr. **Tesar**. Friction aware and lubrication.

Mr. **Gore**. Well, that is fascinating testimony. Thank you very much.

Mr. Scheuer is recognized for 5 minutes.

Mr. **Scheuer**. Yes. Just a brief question for starters, Mr. Tesar. Are you familiar with the computer center in Paris?

Dr. **Tesar**. No, I am sorry I am not.

Mr. **Scheuer**. The World Micro Computer Center. You are not.

Dr. **Tesar**. I just admit I am a mechanics engineer and tend to gravitate toward that.

Mr. **Berg**. The director of our institute, Professor Reddy, is a member of the institute.

Mr. **Gore**. He was a witness here before the subcommittee last week. A fascinating fellow.

Mr. **Scheuer**. I would simply ask if either of you would like to address the questions I asked before: First, what is the role of Government in moving us forward and do we have a problem of acceptance of the whole role of robotics by members of the labor force who feel threatened by it, and if we have, what do we do?

Dr. **Tesar**. I will like to address the Government role question. I have dealt with this quite a bit, interacted with policy people as well as industry people extensively.

I believe that our biggest failing in this area is first organization, sense of purpose and sense of urgency.

Second, recognizing management of the task. In the United States, it is very high, management level is very low. We have to get industry, universities, and Government active so that things actually happen on a negotiated basis. That means all universities would have to be involved to a certain extent and not be an isolated few.

That is one of our biggest problems, that an isolated few are involved. There are a lot of wonderful universities that get left out, underutilized to our great deficit in this country.

Mr. **Scheuer**. Thank you.

Mr. **Berg**. I would like to make a few comments.

I think my experience with labor indicates to me that they are scared, and I don't blame them. We don't know what is going to happen; they don't know. They see tremendous world competitive pressures; it is a time of transition, obviously. As a result, of our concerns, we have enlisted labor unions in our societal impact study; but that is really only a start.

I guess I will repeat what I said before: labor uneasiness clearly is an issue: labor is scared; there is much more in this area that we must understand and much more that we must do.

Mr. **Scheuer**. We didn't get the feeling from the other panels and issues that it was an issue.

I asked the question in several different ways, and we got repeated answers that labor is happy with robotics, no apprehension, all systems are go. You are the first witness today who seems to indicate that there may be a problem of acceptance and anxiety or anxiety and therefore reluctance to see it move ahead.

Dr. **Berg**. We talk about going to a different kind of society where the labor force is working perhaps a few hours a day, perhaps even a few hours a week. Clearly, there will be tremendous dislocations and reorientations. How we get from here to there, no one at this point knows.

Mr. **Scheuer**. Thank you very much, Mr. Chairman.

Mr. **Gore**. Dr. Horn, would you want to respond?

Dr. **Horn**. No.

Mr. **Gore**. Mr. Volkmer.

Mr. **Volkmer**. I would just like to inquire of Dr. Tesar to expand—do you envision that we get the direction we need in this country by the combination of Government and industry and the universities?

Dr. **Tesar**. Well, I think, first of all——

Mr. **Volkmer**. We have no central organization.

Dr. **Tesar**. That is correct, we do not have a central policy. That is essentially the case. If you look at the NASA/Science Foundation as the representative agency, that covers a broad spectrum of technologies.

One would have to admit that they don't have the resources to carry out that broad mission. It would be impossible for anyone to suggest that NASA/NSF is powerful enough in the area of engineering to carry out a mission that would be equivalent to that of some of the Japanese missions that have come along with cooperation of industries and universities.

The Japanese missions are very structured by comparison, and they forecast what they will do and stay on target, and there is an urgency to do so.

I really wished that we could take advantage of our resources. This country has unbelievable resources in universities and manpower in teaching, education, and distributive industrial research bases, but they don't seem to get together.

It has to be done by negotiated distributive response through incentives, through sense of urgency and purpose. I don't see that coming from any place else but from the Government.

Mr. **Volkmer**. You have had some success, as I understand, in being able to solicit industry to——

Dr. **Tesar**. Nominal success, yes. From industry.

Mr. **Volkmer**. Not that great?

Dr. **Tesar**. You have to be aware of the fact that only 2 or 3 percent of the R&D money in the universities comes from industry, only 2 or 3 percent.

Mr. **Volkmer**. You see no fear in having that enlarged?

Dr. **Tesar**. I have no reservation whatever. I feel my priorities are established by industry. I have a better sense of purpose in direction than I would get otherwise.

Mr. **Volkmer**. All right.

Do you think that Government should try and focus on the problem of trying to centralize it through the Congress or through a Presidential commission or something like this?

Dr. **Tesar**. Yes, sir. I think that the country should say this is our purpose, we want industry and the universities and other laboratories to get together, we will provide sufficient incentives to allow negotiated distributed response and if you look at the way industry responds to policy and with that policy industry will respond in a positive way with a good policy.

If the Government says we will let certain dying industries die, the signal is very clear.

Mr. **Scheuer**. Will my colleague yield?

Mr. **Volkmer**. Go ahead and I have one more question.

Mr. **Scheuer**. We have a recently appointed Commission on Productivity. Would that be the engine that Congressman Volkmer is looking to to focus our concern?

Mr. **Volkmer**. That was my next question—not exactly that, but go ahead.

Mr. **Scheuer**. No, no, there is one possibility there.

Dr. **Tesar**. Yes.

Mr. **Scheuer**. Or are there reasons we need something else?

Dr. **Tesar**. I have watched this for some years, and most of you have, but it seems every time we have a new Commission or study, we don't seem to bite the bullet. The Commissioners went through this last year—in the last administration, I suspect it went on before that.

So I think that we have got to get over this. We have to get to the sense of urgency.

Mr. **Volkmer**. Let me ask you one last question, and it would be a hypothetical, it is one of those "if" things, you know, a little word. But let's assume the United States had manufactured mechanical robots, was in the same position to use the robotics as they are in Japan.

Would you tell us where we would be as far as manufacturing and the cost of manufacturing, et cetera?

Anybody want to try that?

Dr. **Tesar**. I suspect the major benefit would be improved quality of product.

Mr. **Volkmer**. More in quality than in costs?

Dr. **Tesar**. That was my first reaction, yes.

Mr. **Volkmer**. Anybody else?

Dr. **Horn**. Well, I agree with Dr. Tesar, that somehow we have got to elevate this to the status of a national need, so that it is recognized that we should be working on it, and that something that will be supported for a substantial amount of time, so there is some security in its future.

As far as where we would be if we had the widespread introduction of simple robots as we do in Japan, I agree that perhaps the primary interface would be in quality. On the other hand, improved quality usually also means reduced cost, because if you make 100 things and 70 aren't right——

Mr. **Volkmer**. You don't have the recalls and you don't have to go back over and redo.

Dr. **Horn**. Right.

Mr. **Volkmer**. Thank you, Mr. Chairman.

Mr. **Gore**. Well, I get the impression that the Government effort in this area is akin to one of your first-generation robots. It is pretty awkward, it doesn't get feedback, it doesn't move in very many degrees, not very sophisticated.

Dr. **Tesar**. I love that analogy.

Mr. **Volkmer**. Very slow moving.

Mr. **Gore**. That is right. You have to walk it through.

Mr. **Rosen**. And it shakes a lot.

Mr. GORE. Yes, it shakes a lot. This year, it will shake a lot of heads.

I won't torture that metaphor any more. Seriously, we do have to improve the function and role of the Government in this area rather quickly if we are going to compete with Japan and other countries.

Let me start in a slightly different place. Dr. Horn, and maybe the other two witnesses would like to respond to this, I don't know to what extent you gentlemen feel expert in artificial intelligence.

Dr. Horn, you are from the Artificial Intelligence Laboratory; let me ask you the extent to which you believe artificial intelligence will advance in the balance of this century.

Dr. HORN. Well, I think that as far as robotics is concerned, we don't really look for tremendous advances in AI, even if we use what is available now.

Also, robotics seems to require new things. For example, it was felt for a long time that the special reasonin problems I talked about could be solved by traditional AI methods that are now used in other problem-solving contexts until we tried it and found that special reasoning was something we had to address on our own.

I think that artificial intelligence and its application to robotics will make great advances. It has done so already in areas where people have built expert problem-solving systems for specific domains such as geologic explorations and disease contexts.

It has made natural language interfaces for other systems, so they are more widely available. There are systems which allow you to retrieve information, management information-type systems which would not otherwise be used because managers do not like to learn the programing language.

By providing the natural language interfaces now, they are more widely accessible and frequently, in fact, the natural language interface is the most expensive component, and the largest part of the system.

But it is making a great impact already, whereas, for many years, AI was just a glint in our eyes and far off into the future. It has gotten to the point where it is commercially feasible to exploit some of these ideas. Companies are being formed.

Mr. GORE. Dr. Berg?

Dr. BERG. I would like to endorse what has been said and give a slightly different perception of it.

There is a tremendous wealth of basic research involving AI already developed and just beginning to be used. I think that research relates to the kind of robotics we have talked about; namely, there are a number of companies that are using artificial intelligence for maintenance systems. They are planning to put sensor-based systems on machinery which will use the information collected. Initially, humans will look at that information, then get access to the artificial intelligence system to tell it how that machinery has to be maintenanced. Eventually, however, the sensor based system will act on its own.

So there are a lot of things just coming to the fore based on past research in AI. In addition, I have to mention that one of my colleagues has said he likens what is going on to what happened in the British industrial revolution in that the driving force for the development of steam engines was the pumping of water out of the coal mines. It was the study of steam engines that in time led to the real development of the science of thermodynamics. So, the driving force for a lot of basic research is practical problems; the same is happening now in AI.

Mr. GORE. Well, complete the analogy, what is the driving force?

Dr. BERG. He is predicting that because of the driving force of using these AI systems to respond to practical problems, the whole field of artificial intelligence will develop a deeper scientific underpinning.

Mr. GORE. That is the larger question precisely that I am getting at. Is it theoretically impossible for a machine to become conscious?

Dr. BERG. Well, there are great debates in this area of what thinking means and I guess I am not qualified to judge. I might note that the machines appear as to go through some reasoning process which is different than what humans do. It is—in terms of the machine operation—different, but it has gone through some kind of process which enables it to make a decision, which makes it appear it has intelligence, but it is of a different kind.

Mr. GORE. Dr. Horn?

Dr. HORN. Well, I think that perhaps I would like to concentrate rather on those uses of AI which don't go quite that far. There are many things we can do which don't involve——

Mr. GORE. I know it is a tangential question, but one I was interested in.

Dr. HORN. I would like to answer by saying it is difficult to define something that is "conscious" just as it is difficult to be sure what is "live" in the sense that to external stimuli, something reacts in what appears to be an intelligent way, you might conclude it is intelligent in the same way you conclude something is conscious.

I don't think there is a good answer to that. As far as the research is concerned, I guess the hope is that one would continue and develop science fiction-type creatures, but I am not interested in that.

I think we can do a lot of really neat things in the closer term with the techniques we have developed.

Mr. GORE. Has any research been done on the relationship between energy use and robotics, specifically, the improvement or lack of improvement in energy use compared to a human system?

Dr. TESAR. May I mention something about that? Generally speaking, robotics themselves, if that is all you are looking at, are extremely energy-intensive. They are almost without a doubt the most energy-intensive machines you could have.

On the other hand, if you look at the total system, part of the system has support to the more complex system, it may be much more energy-efficient.

So I could say a robot could be 1,000 times less efficient as far as energy use than a direct machine. I would have no reservation about that kind of number.

Mr. GORE. Dr. Horn, Dr. Berg?

Research has not really been done on this question.

Dr. TESAR. That is right.

Mr. **Gore**. If we stand, as some Americans believe, on the verge of a third energy shock, that question could become a significant one.

Dr. Berg, how has the arrangement between Carnegie, Mellon and Westinghouse worked out? Are you satisfied with that arrangement?

Dr. **Berg**. I can't speak for Westinghouse, but based on all we have seen, I think the agreement has worked very well for both parties. I should mention that Westinghouse is not the only participant in our Robotics Institute. They were the first major one. Since then, we have had at least two more major supporters, Digital Equipment Corp. and the Office of Naval Research. We also have about 15 industrial affiliates, so we have a varying degree of participation. Westinghouse happened to be the first and the largest. From what they tell us, in fact, they are going to continue to fund us and to work closely with us. I would say it has worked out very well for them as it has for us.

Mr. **Gore**. You haven't felt your institutional priorities have been changed in a detrimental way?

Dr. **Berg**. Not at all. If I can take a moment, I'll tell you how we operate. We have selected the problems that we work on by asking Westinghouse to come up with a list of about 25 things that they would like to see solved, 25 problems that they felt were significant. Out of that 25, we have selected 3 or 4 that we felt were important and that we could do.

Subsequently, we have been able to do research relevant to us both that can be shared with their people. The research has led to developments that are being incorporated into their production facilities. In addition, as I stated before, they have gotten the patent rights to significant numbers of patents and software copyrights already, and we have published papers fulfilling our function.

Mr. **Gore**. Dr. Tesar, let's suppose for a moment that your 10 centers are not set up and that the U.S. Government's effort remains relatively small and uncoordinated. What is the concern—what is the problem with that?

What I am getting at is, how big a threat is there that the use of robotics in other manufacturing countries will deprive us of many millions of those jobs now available?

Dr. **Tesar**. I think the crucial question is jobs, and as you know, the policy, I should say perhaps, business climate, in the Northeast is not as attractive as it is in the Southeast.

So there has been very rapid movement of jobs from the Northeast to the Southeast over the last decade.

Now, it should be possible to recognize that international competition has the same influence and impact, that if you do not have a vital atmosphere, that means people and technology at all levels, industry which has to take the position of survival will make the most effective decision at a different moment to maintain that survival.

Whether it has to do with national interest or not is not really the crucial question.

Their survival is the prudent question. So if the national Government does not establish policy where the vitality of people in technology is available so industry, when it needs those resources, can absorb them and move with opportunity and urgency, it will take the secondary road which is to lose the jobs, transmit the more expensive task to other countries and in many ways maintain marketing capability in this country, and not a manufacturing capability.

I am very concerned about that. I think the vitality of the technology and the growth of the people is a Government responsibility.

Mr. **Gore**. I certainly appreciate the amount of thought you have given that question, and as I said earlier, I think we have to rapidly improve our Nation's ability to perform this task.

Dr. Horn, my final question, do you believe that the U.S. robotics research effort has fallen behind the Japanese?

Mr. **Horn**. No, it has not, because the strength of the Japanese is in the mechanical side, and widespread use of the robot, they are weak at the moment in computer science and development of algorithms.

However, on my last visit, I saw disturbing signs where they developed CADCAM systems comparable to our own. I think they could catch up on us particularly with these large Government projects like PIPS and the problem sponsored by MITI now.

At the moment, we may feel safe, but that is not going to last long.

Dr. **Tesar**. May I comment, when I was in Japan last week, there was a newspaper article saying they are going to put $400 million in the next 10 years into software development.

Mr. **Gore**. Well, to draw another analogy, I have done a lot of work in strategic arms and you see the payoff in research effort and deployment of new equipment altering the strategic balance. When you look at the balance of trade and the balance of manufacturing capability, the deployment of robots is a critical factor in affecting that trade and the allocation of research money and the focus of research effort on areas that have the ability to confer a dramatic trade advance is something that this country can't sit back on and take in a blythe way what is happening.

We have to compete. In order to compete, we have to recognize, in my judgment, that we have to work together and that that means often we have to work together through the Government focusing intelligent efforts to make the transition which lies directly ahead.

Did you want to ask another question before we go to our discussants?

Mr. **Scheuer**. No.

Mr. **Gore**. Dr. Sanderson

Dr. **Sanderson**. This panel has emphasized the need for continuity and for a level of resources to be focused on this problem area. One issue of interest to me, is the resource limitations which exist. This of course, is a budgetary issue which has to be examined by each Congress and by each administration in terms of national priorities.

Many of the areas which have been discussed are areas that the Foundation or other Federal agencies have been actively working in.

Certainly, in the engineering directorate, we place a lot of emphasis on the support of fundamental research activities.

We have also sponsored the development of some centers in robotics or in other technologies. We have actively encouraged formation of industry-wide cooperative programs such as the cooperative program in the chemical industry and many of the centers now being established in microelectronics.

Where do you think the priorities should be placed in the Federal Government in terms of achieving the greatest forward momentum in this area of robotics and the implementation of robotics into our economy?

Dr. TESAR. Why don't you go ahead?

Dr. BERG. Well, Dr. Sanderson, at least what I think is happening is that a lot of the DOD related agencies are getting very active in this area. If I look at our own experience, I think the support that we have received for pattern recognition work from the Defense Advanced Research Projects Agency has been key in giving us a firm scientific foundation for the work we are doing.

I don't think that commitment has a broad enough impact on our industrial base. I think that it encourages only a certain group of industrials to get involved in robotics research. I guess the question that I am not sure I am qualified to answer is how do you get a broad range of companies in this country to become aware of and committed to incorporating the results of robotics research into their own operations.

I guess I don't know the answer.

Dr. HORN. Well, I think related to the problem of a lot of robotics research having been funded by DOD is the similar situation that occurred with NASA, where certainly robotics and artificial intelligence would be of great value to them, but they have had not the resources to do it themselves, but worked on the basis of others doing it.

This has not materialized because problems were different. Similarly, the problems of industrial robotics are just a little different than we raise in our research funded by DARPRA and RNR. I think there is a need to strengthen the civilian component for funding for robotics. I think NSF would be the appropriate place to do that, both in terms of strengthening existing centers working in robotics and in establishing new ones.

We don't have the number of people being trained now that we need and that will only happen if new places also start.

Dr. TESAR. Well, that is a very difficult question to answer. But, obviously, I think if I had my choices, first of all, NSF does not have enough research dollars. It is clear they don't have the money for the job.

We have to be aware of the fact that 250 engineers schools which represents perhaps 2,500 departments, is spending $90 million over 2,500 departments representing about $30,000 a department.

I appreciate the fact you don't put salt on top of salt or grains on grains of sand on top of the beach. The management of the problem is significant just in engineering.

I think we have to face the issue that the very best way is create incentives for industry to interact, not only with Government labs, but the universities have to be in the picture.

I think it fits beautifully into the present administration's philosophy. I think it can be done. There are certain significant barriers at every State line that allows industry and the universities in that particular State to want to cooperate with each other and I think we can enhance that by having properly established incentives from the Federal Government.

If you have only 2 or 3 percent of all your R&D money now coming from industry, you do have a decoupled system which is not working together, the customer is not being listened to and the university is not establishing priorities in concert with the needs.

Dr. SANDERSON. I am glad you emphasized that point. There have been a number of changes in the tax laws in the last year or two. There have been a number of States that have grown increasingly concerned with their own economically competitive capability and in which the State governments or the industries within the States have begun to take action.

It has been most visible in microelectronics. Are you seeing any similar signs in the area of robotics? And if so, do you think this is the beginning of the solution?

Mr. TESAR. I think Carnegie-Mellon is a good example, but the fact is that the State of Florida is one of those emerging States which is becoming more conscious of how you bring industry in and how you make yourself more attractive.

Right now, the State of Florida has the best business climate in the United States.

Mr. GORE. No; the second best.

Dr. TESAR. Oh, OK. We are similar in our natural resources to Japan, so therefore, we have to structure ourselves in many ways that Japan has. The State authority is now acting to take those steps.

Dr. HORN. Just one last comment, I think it would be advantageous if it were possible for companies to cooperate on research than we can under current law. I don't know how you change that.

Mr. SCHEUER. May I?

Mr. GORE. Sure.

Mr. SCHEUER. There is thinking going on along those lines. As a matter of fact, there was a meeting recently between several Members of Congress and Department of Justice officials, the head of the Antitrust Branch, the top official of the Office of Management and Budget, somebody representing the President from the White House, and an Under Secretary of Treasury, on just that question.

How can companies pool resources and pool capital for R&D and not come afoul of the antitrust laws.

There is a growing perception that that is absolutely necessary for us to compete, especially with the Japanese where that cooperation between enormous corporate entities in Japan is not only permitted but encouraged and funded by their Government.

At least in R&D I think there is a growing perception that we have to permit that cooperative action in R&D and there is a lot of ferment going on, as I said, along that line.

Dr. SANDERSON. Mr. Scheuer, that is an area that is also under considerable discussion in the National Science Foundation.

Indeed, there are questions about the ways that one can encourage cooperative R&D activities and there is discussion going on with the Justice Department and the executive branch as well.

Mr. **Scheuer**. One simple way to encourage it is to say that it is legal instead of illegal.

Mr. **Sanderson**. There are questions going even further than that, and that is that many of our antitrust laws were put in around the turn of the century, when the United States was very much an insular economy and when the cost of transporting manufactured goods often exceeded the value added in the manufacture.

Today you can pick up an integrated circuit chip and mail it from here to Japan for the cost of a postage stamp. As long as one is maintaining a free-market economy, the antitrust issue takes on a very different complexity because we are no longer as worried about the same internal cartel formation.

Mr. **Scheuer**. What we are worried about is not just competition in the United States, not just where we can maintain an economy with three or four automobile companies, but rather in terms of a global way, whether any automobile company will be able to survive or whether any telecommunications manufacturer will survive in the face of global competition.

One of the ways in which we may enable our automobile industry and our steel industry and our telecommunications industry to survive at all in this now-global market is to enable them to pool resources.

So, the whole thrust—this is not to reflect on Al Gore and my predecessor of almost a century ago, I don't suppose today we are any more omniscient of what conditions will be in 2080 or 2090 than they were at the turn of the century about conditions today—but the form that the antitrust laws take today are totally archaic and anachronistic and irrelevant and harmful to the sharply tuned analysis of what our industrial problems are today, and what our real problems are in the sense of America surviving as a major factor in a global economy.

That, as I said before, that thinking is permeating this Government, and there is considerable ferment.

Mr. **Gore**. I don't want to break the harmony, but in my opinion a lot of the concerns which led to the formation of the antitrust laws around the turn of the century and for decades after that still exist, and although some of the applications of the antitrust laws have caused difficulties, I think the problem of concentrating power in the economy is still a very keen problem that has to be faced.

I think some of the antitrust laws need to be strengthened rather than weakened. All of them need to be made more efficient and more relevant.

Certainly, that is a ground on which we can agree. But I, for one, want the record to reflect some concern that we not abandon the protections that were important then and are still important today.

Dr. **Sanderson**. Mr. Gore, certainly I cannot speak as an expert in the antitrust area, and the concerns for concentration of power are very real, but at the same time, I think the mechanism by which we prevent undue concentration of power may be inhibiting our ability to cooperate in areas where cooperation would be beneficial.

Certainly, the ability to cooperate in R&D could enable a great deal of forward advancement in our technical capability, by not looking at internal competition of the United States and Japan, but their ability to compete against one another in Third World markets.

One point made is that the Japanese are often able to provide a much more integrated package of all the capabilities needed to deliver the end products than the United States because of our real or imagined concerns with antitrust.

Many of them I suspect are imagined concerns.

Mr. **Gore**. We are going to have to move along. Dr. Berg, you wanted to react to—you don't?

Dr. **Berg**. No, thank you.

Mr. **Gore**. Dr. Chern?

Dr. **Chern**. I guess the only comment I would like to make is to try to set things a little bit in perspective.

It is true that the robot is a system which performs mechanical activities but I think we should view robotics in many ways as an application area of which many disciplines come to play a role, areas like computer science, electrical engineering, mechanical engineering, people who build actuators, and various groups and individuals.

I think what is interesting about the robotics is that many of the problems which will occur when we go toward automated manufacturing, begin to occur in a more constrained way that can be perhaps more easily encompassed and handled in the robotics area.

So, we have talked about robotics and automated manufacturing. They are quite different. Robots are a form of automata, and there are many forms of automata. The problems arise in integrating those things into systems and the problems are formidable. They are not easily solved.

In fact, if you had to really build truly flexible automated manufacturing systems today, we couldn't do it.

We can approximate it so you have a transfer machine in a mechanical sense an automated manufacturing system. There are various degrees of automation, and you have heard about the experiments. I think what is interesting in robotics is it is an area where enormous progress can be made and where there, in a sense, is this competition between the various disciplines which is healthy, I think, and very useful.

So you may get people who look at computer science and computer engineering and they look at it from the point of view of the semiconductor revolution of what we can do in terms of gaining precision by use of feedback and different types of control.

You get the mechanical engineers who look more traditionally at it. They may wish to obtain this type of precision through use of different types of actuators and different types of mechanical structures.

It is an interesting combination that different people view the problem from different perspectives. It is that sort of joining together which I think will yield some very interesting advances.

Mr. **Gore**. Thank you very much.

Dr. Strauss.

Dr. STRAUSS. No.

Mr. GORE. Let me thank all of our witnesses and let me thank this last panel for an excellent job. I would like to also thank our expert discussants, Dr. Sanderson, Dr. Chern, Dr. Strauss. You have certainly contributed to the record today, and helped the subcommittee.

I think it has been a fascinating hearing, and I just want to thank, again, all the witness here today. We have our work cut out for us in focusing the Government's effort in this area, and it is an urgent and important task.

Thank you all for your helping us address it.

[Whereupon, at 2:25 p.m., the subcommittee adjourned subject to the call of the Chair.]

ROBOTICS

WEDNESDAY, JUNE 23, 1982

House of Representatives,
Committee on Science and Technology,
Subcommittee on Investigations and Oversight,
Washington, D.C.

The subcommittee met, pursuant to recess, at 9:45 a.m., in room 2325, Rayburn House Office Building, Hon. Albert Gore, Jr. (chairman of the subcommittee) presiding.

Present: Representatives Gore and Walker.

Mr. Gore. The subcommittee will come to order.

I would like to welcome all of our witnesses on this giant panel and all of our guests. This is our second hearing on robotics and the implications of robotics. At our hearing on June 2, we heard from three panels of experts who discussed the projections of foreign industry, U.S. industry, and universities for the use of robots and their perspectives on the development of robotics technology. It was a fascinating hearing but the record would not be complete without the Government witnesses who will be testifying today.

In order to put today's testimony in perspective, I would like to very briefly highlight some of the testimony from our subcommittee's June 2 hearing. We learned that there are approximately 14,000 robots in Japan, 6,000 to 7,000 in the Soviet Union, and 3,000 in the United States. By 1985 there are expected to be 85,000 to 100,000 in Japan, 40,000 to 42,500 in the Soviet Union, and only 15,000 in the United States.

The importance of robots lies in their ability to increase productivity. Unlike humans, they do not need coffee breaks, vacation, or sleep, as many of our witnesses noted. They can work continuous shifts, doing monotonous work without tiring. Extensive use of robots will have major impacts on productivity. Indeed, those impacts are already evident. It could create jobs but of course they also have great potential to displace millions of workers. The extent of such displacement is not clear but what is clear is that robots will dramatically alter employment patterns in at least the basic industries like the automotive industry. Any plans for increased use of robots, therefore, needs to be extremely sensitive to such concerns.

As we learned in our hearing earlier this month, the Japanese have embarked on an aggressive program to develop a preeminent position in the development of robotic technology. Back in 1977, Japan launched an ambitious project to develop an automated factory or automated manufacturing system, or FMS. They have made excellent progress, apparently, and they appear to be much further along than the United States in the development of an automated factory.

This past year the Japanese Ministry of Trade and Industry or MITI initiated a 7-year national robot research program to develop Japanese self-sufficiency in robotics technology. I saw on television two nights ago the robot pilot of one of their ships. I do not know if anybody saw that, where the captain of the ship spoke commands in English and the computer and robot controls made the ship do whatever he said.

Strong support by the Japanese Government of robotics has included development of the Japan Leasing Corp., established to assist companies who want to lease robots; second, provision of low-interest loans to small- and medium-size firms to encourage the use of robots; and, three, allowance of an extra depreciation for use of robots. Similar efforts have been made in some European nations.

United States industry and major U.S. universities are actively conducting robotic research but, as we have heard, their efforts are not nearly as coordinated or as well financed as are those of the Japanese and other industrialized countries. Clearly more can and should be done.

Earlier this month the subcommittee's witnesses suggested ways to improve the U.S. robotics effort. Suggestions included the development of a national robotics plan; incentives for improved Goverment-industry-university coordination; and establishment of robotics centers. The purpose of today's hearing is to examine these and other suggestions in order to determine what role the Federal Government can best play in this area.

It is, therefore, appropriate that today we hear from robotics experts in the National Science Foundation, the National Aeronautics and Space Administration, the National Bureau of Standards, the Department of Defense, and the Office of Technology Assessment, to assist in further assessing the following questions: One, is there a need for a national plan to promote robotics technology? Two, what is the Federal role in the development and application of robotics technology? Three, what is the Federal role in evaluating the potential employment impacts from the widespread use of robotics technology and in stimulating programs to reduce adverse impacts? Four, what is the nature of robotics research being conducted and/or funded by the Federal Government? Five, what are long-range research projects that should be funded by the Federal Government? And, six, what efforts are being made to coordinate Federal robotics research?

I look forward to a vigorous discussion of the feasibility of developing a national plan and on the other suggestions that encourage closer cooperation between industry, universities, and the Government.

I would like to ask unanimous consent at this point that the record be held open for the inclusion of the opening statement of the ranking minority member, Mr. Walker.

[The opening remarks of Mr. Walker follow:]

OPENING REMARKS OF ROBERT S. WALKER

Mr. Chairman, I would like to join you in welcoming the witnesses here today. This area is one in which the role of government is not yet clear.

For many years America's leadership in world markets was taken for granted in this country. But we are now learning that our leadership has been seriously eroded in many areas.

In our first hearing on this matter we learned that the Japanese have taken a clear and commanding lead in the field of robotics. And, what may be even more serious, is that the Japanese lead is rapidly increasing.

One of the most serious problems facing American industry is the relatively high cost of skilled American labor. In many other parts of the world labor costs are so much lower that there is a competitive advantage for goods produced overseas.

But, we have learned from our own limited experience with robotics, and seen in a much larger scale in the Japanese experience, that robots can replace manpower in many repetitive applications. So far, the general experience has been that the introduction of robots has considerably increased productivity and freed human labor for other applications in the production process.

Today, we will hear from a number of government witnesses who will discuss robotics in the government. Perhaps, after having heard from the government we may be able to determine what the proper role of government in this area will be.

There are a number of possible areas in which the government might become involved, including: Research on basic robotics, development of particular techniques and equipment, implementation of robotics technology through tax incentives or other incentives, education in basic robotics and possible retraining assistance.

We have learned a great deal about the ability of man to design machines to do complex tasks in all possible environments. We merely have to look about this room to see a number of the most spectacular applications. Now that we have the basic technology, we can and should be ready to utilize it for the good of all mankind.

Mr. GORE. I would like to welcome our witnesses today. We just have one large panel. Only five of the witnesses at the table have prepared statements, I am informed, and others are present to respond to questions and to assist in the presentation of the various departments and agencies here represented.

I would like to welcome to represent and speak on behalf of the National Science Foundation, Dr. Jack Sanderson, Assistant Director of the Directorate of Engineering; to represent NASA, Lee Holcomb, Manager of the Computer Science and Electronics Division of the Office of Aeronautics and Space Technology, who is accompanied by Dr. William B. Gevarter, Manager of Robotics Research, and Dr. Larsen, Manager of Automation and Computer Science; representing the National Bureau of Standards, Dr. John W. Lyons, Director of the National Engineering Laboratory, accompanied by Dr. James S. Albus, Acting Chief of the Industrial Systems Division; representing the Department of Defense, Dr. Edith W. Martin, who is Deputy Under Secretary of Defense for Research and Advanced Technology, accompanied by Dr. Lloyd Lehn, Assistant for Manufacturing Technology in the Office of the Under Secretary; and, finally, representing the Office of Technology Assessment, D. Frederick Weingarten, Program Manager for Communications and Information Technologies.

Ladies and gentlemen, without objection the entire text of your prepared statements will be put into the record in full at this point. We will invite you to go ahead with your testimony at this point. If you want to read your testimony, that is OK. If you prefer to summarize the highlights, that is fine, too.

We would like to begin with Dr. Jack Sanderson from the National Science Foundation.

STATEMENT OF DR. JACK SANDERSON, ASSISTANT DIRECTOR, DIRECTORATE OF ENGINEERING, NATIONAL SCIENCE FOUNDATION

Dr. **Sanderson**. Thank you, Congressman Gore.

In the interest of time I would like to have my formal statement put in the record and to just briefly highlight a few points which I think are important.

The National Science Foundation, as you are aware, has as its primary concern the long-range health of U.S. science and technology, and we support that, in general, through funds for fundamental or longer term research activities and through funds designed to encourage some of our best graduating students to continue their careers in science and engineering.

The area of robotics broadly defined to include automated manufacturing and related activities is one that the Foundation has been concerned with for a number of years. We have had for some time a program concentrated on production research. That program has produced a number of significant results on individual projects and I have some material which I will be glad to supply to you and your staff. This material highlights some of the research activities in production research which looks at the longer-term applications of science and technology to robotics and manufacturing.

We have experimented with the problem of transferring some of this technology into use. For example, we funded a joint university/industry cooperative activity at Westinghouse a few years ago which was designed to pull together the basic research results from some half-dozen projects that we had funded earlier to create an automated assembly system designed to assemble major components of electric motors. This product was selected because many of the steps involved in assembly represent typical manufacturing steps. That particular project is just about reaching completion and we hope to begin publicizing the final results in the near future.

More fundamentally, we have been concerned for several years about the need to build on America's strength in the robotics and automated manufacturing area, that is, the high technology end of the spectrum. We have spent about half a year looking at the opportunities for robotics research, the problems in sensors, controls, computing, and the areas of fundamental research where we believed NSF could make the greatest contribution. We have now produced a program plan to emphasize those activities where we already have fundamental research going on and have begun to pull these activities together so that we can get the interchange of ideas and the interdisciplinary approach that will be needed to really make robotics advance over the long term.

I have a few documents which I have included in the record as part of my formal testimony, highlighting some of those activities. One was prepared by a contractor about 3 months ago which looked at the robotics research and research needs in the United States and attempted to identify not only what the research needs are but also those laboratories currently actively involved in this type research.

A second area of concern, in addition to building the fundamental technology, is the problem of skilled manpower that will be required to operate the factory of the future. In this area, the Foundation has taken two steps, both of which are pointed out in my testimony. First, we have assigned a very high priority to the engineering research programs for which I am responsible and to the related mathematics and physical science programs, so that those are the fastest-growing parts of the Foundation at present. We are also trying to build the research capability of the universities in order to produce better students and to produce a stronger base of fundamental research in the universities.

Wherever possible we are encouraging the universities to work collaboratively with U.S. industry in joint university-industry activities which tend to strengthen the transfer of the fundamental research going on in the university and move it more quickly into use.

Second, we, like many of you here in the Congress, have been concerned with the falling test scores, the declining scientific aptitude, of many of our secondary school students. As a result, we announced about a month and a half ago the establishment of a special Commission on Precollege Education in Mathematics, Science and Technology. That Commission has been charged with producing an action report within the next 12 to 18 months in an attempt to identify key steps that can be taken by the Federal Government, by local school systems, and by State systems, to reverse the downward trend in test scores and to try to improve the scientific and engineering aptitude of the high school student so that he or she has a greater range of career options.

I will be glad to respond to questions, and I would like to provide your staff with much of the documentation which we have developed in this area.

[The prepared statement of Dr. Sanderson follows:]

STATEMENT OF
DR. JACK T. SANDERSON
ASSISTANT DIRECTOR FOR ENGINEERING
NATIONAL SCIENCE FOUNDATION

BEFORE THE

SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

JUNE 23, 1982

Mr. Chairman and Members of the Subcommittee:

It is a privilege to participate in this set of hearings on robotic technology. Robotics, broadly defined to include intelligent machinery and automated manufacturing, has the potential of causing major changes in the way products are manufactured and in economic competitiveness of industry. The impact of these changes could rival that of the industrial revolution, and are as unavoidable as the earlier industrial revolution for any nation that wants to become or remain a world technological leader.

Your first day of hearings identified many of the key policy issues that will be addressed.

MANPOWER

Job creation, worker displacement and related educational, social, and economic issues are of great concern but are only partially understood. Without doubt, jobs will disappear. Some already have -- usually those that are most hazardous, strenuous, tedious and boring, e.g., the current application of robotics to painting, welding, and handling heavy components. At the same time many jobs are also being created, not only in the design and manufacture of robotics systems but also jobs in operating, adapting, and maintaining new systems in the work environment. While we cannot neglect the high personal loss to the individual displaced worker which sometimes arises, the net loss of job and personal income due to robotics is likely to be substantially less than potential losses caused by the failure to take advantage of modern technology and the substantial loss of ability to compete in international markets. Both industry and society have the responsibility to provide the educational support and training needed to upgrade displaced workers and to provide the highly skilled manpower needed by modern industry.

At the National Science Foundation we have two areas of particular concern: the strengthening of our engineering schools and the quality of precollege education in mathematics and the sciences. The National Science Foundation is currently assigning high priority to research programs in engineering and the mathematical and physical sciences, particularly computer research. We have also established a major Commission on Precollege Science Education with the responsibility to recommend appropriate actions in order to reverse the downward trend in science aptitude test scores and to improve the ability of young students for careers in science and engineering.

Over the long term, demographic data indicate that we must substantially increase our national productivity or change the current pattern of work and retirement. Decrease in the birth rate and increased life expectancy following World War II will result in a substantial decline of the percentage of total U.S. population in the work force during the next several decades.

FOREIGN COMPETITION

All evidence indicates that Japan, and possibly some European countries, are planning a substantially greater use of robots in industry during the next decade. While increasing substantially, estimates for the use of robots by U.S. industry are significantly less. The data are clouded, however, by differences in definition about what constitutes a robot and differences in the degree of sophistication of the robots being used. It is clear, however, that the Japanese are gaining significantly in dealing with the problems of systems engineering and developing an experience base through the large number of robots in use. The United States is placing greater emphasis on developing advanced robotic systems with programs designed to develop improved sensors, control systems and highly flexible intelligent manipulators. This is an area where we have a significant advantage that could prove decisive over the long term.

We are not without competition here, however. The Japanese have major research programs in these same areas. Also, a member of the NSF engineering staff, on a recent visit to robot installations in France, was highly impressed with the quality of research and technical competence of the French efforts.

U.S. GOVERNMENT ACTIVITIES

Mr. Chairman, your letter of June 14 requested information about the nature of robotics research in the Federal Government. I am not competent to describe, in detail, the total Federal effort; however, I am aware of significant research programs being planned or underway in the Office of Naval Research, the Army Research Office, and the Department of Energy. These programs are aimed at the development and application of robots in hostile environments, such as underwater, in space, or in areas of high risk to human health or life. The Foundation is coordinating its fundamental research program in robotics with these agencies, both at the program officer level and at the planning level by the agencies. I have personnaly met with representatives of the Office of Naval Research, the Bureau of Standards, and other groups such as committees of the Army Science Board to discuss the NSF program and how it relates to their activities.

LONG-RANGE RESEARCH NEEDS

Robotics research is synergistic; it relies heavily on a variety of project areas. At a minimum, the long-range needs in such research have to include the following:

- o Sensors and controls. Research is needed on sensors, including touch and vision, pattern recognition in two and three dimensions; sophisticated control systems for sensory equipped manipulators; and problems associated with the robot as a system.

- o Computer engineering. An especially critical area is research relating to computational issues that are needed for intelligent robotic systems, specifically, new high level computer languages; special microprocessors for real time computing; and distributed processing systems based upon VLSI technology.

- o Systems problems. There are unsolved problems in large-scale systems consisting of manipulators coupled with computer controlled machine tools; static and dynamic scheduling problems; problems of machine and system failure; and system organization.

- o Computer intelligence. Advanced robotic and automated systems require knowledge about computer-based systems that have some of the characteristics of human intelligence, including the ability to adapt to changing environments. These systems use vision and other sensors and capture human expertise about the jobs to be carried out.

- o Manufacturing engineering. Further efforts must be made in production planning and control, factory system engineering, workplace engineering, engineering economics in the factory, and fabricability of engineering materials and machining.

- Mechanical systems research. A complete program to strongly reinforce other areas of automation research should include: efforts in machine dynamics, including dynamics of robots, mechanical elements for robots, and origins and control of machine noise; research tribology, including friction and wear in mechanisms, automatically-controlled machine lubrication, and long-life rubbing seals; and studies on major elements of design, including integration of software programs into comprehensive product design systems, high reliability components for operation of unattended machines, low friction power trains, high-speed and high-load spindles, high-accuracy actuators, and microprocessor-controlled machines with self-diagnosing capabilities.

- Organization and human factors. New technical systems, such as intelligent machines and machine systems, will drastically alter the relationship between people and the machine. Better models are needed to examine the interaction between new mechanical systems and the organizations into which they are introduced.

- Information research. Flexible manufacturing systems and automation present serious information structure and retrieval problems, particularly those involving natural language access to data bases and systems.

- Implementation of new technologies. The implementation of new technologies and manufacturing innovations proceed much more slowly than the advances in the technology itself. Many reasons have been proposed to explain the lag. There is a serious lack, however, of scientific data pertaining to the implementation process, and about what sorts of private and public policies might hasten the use of technology.

The National Science Foundation currently provides some support for fundamental research relevant to robotics development in a number of these areas. Although many projects are in Engineering, there is also substantial support from the Mathematical and Physical Sciences and from some areas in Behavioral and Social Sciences as well. I would like to provide, for the record, as part of my formal testimony, a listing of the total amount of project support in FY 1979, FY 1980, and FY 1981. Also, I am including a list of the specific projects for the most recent year, FY 1981. These lists were developed as part of the NSF internal planning process for robotics related research.

Emphasis on basic research in artificial intelligence, distributed computing, control systems, sensors, mechanical design, and systems design has been recommended and approved by the National Science Board. These areas are key to developing highly sophisticated robots that will be needed in the future. In addition, NSF has supported a program of production research for several years. This program is designed specifically to build the technology base needed for fully automated manufacturing. I will be happy to provide you or your staff with copies of Proceedings from several annual conferences on production automation which have been sponsored by this program.

In addition to research project support, there would, of necessity, have to be mechanisms in place to ensure the optimal balance among such areas. Such mechanisms might include:

- Robotics Centers. Such centers might serve as a focal point and coordinating mechanism for the many research areas. These centers would be identified competitively and they would be institutions where substantial research strength and breadth already existed.

- Industry/University Research Coupling. Both academic researchers and industry personnel might participate on the research team, contributing to project design and data analysis as well as to data acquisition. These projects would encourage greater industrial participation in fundamental research and contribute to industry/university networks and technology transfer, with industry bearing a substantial amount of the funding.

- Industry/University Fellowships or Internships. Graduate students and/or faculty members spend one or more years working in industry, making use of the facilities and learning about industrial perspectives and approaches. Industry researchers or managers could, similarly, spend time on university faculties, thereby bringing real world experiences into undergraduate and graduate education. Industry would contribute to the support of this program.

- Small Business. Additional priority might be given to research proposals in the areas identified above by the existing NSF Small Business Program.

- Improved Communication. Workshops and conferences to bring together industrial and academic researchers and managers to define problems, identify research needs, exchange information, and evaluate programs might also be supported. This could be one of the most important components, for through this mechanism it is possible for a consensus to be reached on important and needed research directions. In addition, a continuing committee of academic, industry and Federal agency representatives might be established, possibly under the aegis of the robotic centers or an appropriate professional society, to provide programmatic advice and to encourage industrial support and coupling to the university research effort.

INDUSTRIAL PARTICIPATION

Currently, and where appropriate, industry is already being involved in the NSF program through joint university/industry research projects, the use of industrial advisors or individual programs, and through industrial participation in NSF sponsored workshops and conferences. The Foundation is maintaining close contact with counterpart individuals in the Department of Commerce concerned with the implementation of robots and increased industrial productivity.

In summary, we are enthusiastic about the potential of robotics both as a research challenge and as a potential contributor to U.S. manufacturing capability. We believe that NSF has a significant role in developing and maintaining the fundamental knowledge base that will be needed in this area.

Thank you.

SUMMARY OF AWARDS IN ROBOTICS BY PROGRAM - FY 79, FY 80, AND FY 81

(IN THOUSANDS OF DOLLARS)

PROGRAM	FY 79		FY 80		FY 81	
	# AWARDS	AMOUNT	# AWARDS	AMOUNT	# AWARDS	AMOUNT
MATHEMATICAL AND COMPUTER SCIENCES						
Intelligent Systems Program	5	525.1	6	655.7	2	110
ELECTRICAL, COMPUTER, AND SYSTEMS ENGINEERING						
Computer Engineering	N/A		4	238.0	11	955.8
Automation, Bioengineering and Sensing Systems	14	1,093.7	14	1,241.4	11	751.7
MECHANICAL ENGINEERING AND APPLIED MECHANICS						
Mechanical Systems	3	557.3	6	337.5	13	662.6
Production Research	17	2,521.2	10	1,266.4	9	2,108
INDUSTRIAL SCIENCE AND TECHNOLOGICAL INNOVATION						
Industry/University Cooperative Research Centers	1	627.6	1	303.3	1	455
TOTALS	40	5,324.9	41	4,042.3	47	5,043.1

MCS
Intelligent Systems - FY 81

		Award
MCS-8102874 Shapiro, Linda G Haralick, Robert M. VPI - Virginia Structural Matching and Geometric Reasoning for Object Classification		$60
MCS-8106176 Bajcsy, Ruzena Univ. of Pennsylvania - Pennsylvania Scene Understanding Via Active Sensors		$50
2 Projects	Total	$110

ECS
Computer Engineering - FY 81

ECS-8106686 Price, Camille C. Southern Methodist Univ. - Texas Research Initiation: The Assignment of Computational Tasks Among Distributed Processors with Limited Memories	$48
ECS-8016247 Feigenbaum, Edward A. Stanford Univ. - Calif. Molgen: A Computer Science Application to Molecular Biology	$80
ECS-8016590 Fu, King-Sun Hwang, Kai Briggs, Faye Purdue Univ. - Indiana VLSI Multiprocessor Architecture and Relational Database for Analysis and Management of Imagery Data	$142
ECS Seitz, Charles L. Caltech - Calif. Second Caltech Conference on VLSI, January 1981	$4.8

ECS-8017700 Thomas, Donald Kryder, Mard Carnegie-Mellon Univ. - Pennsylvania Computer Architecture and Magnetic Bubble Memories: An Investigation of System and Technology Level Design Considerations	$88
ECS-8116586 Hayman, Harry IEEE Computer Society - Maryland Travel Funds for the Partial Support of An IEEE Computer Society Workshop (1981 Workshop on Computer for Pattern Analysis and Image Database Management)	$3
ECS-8104646 Voelcker, Herbert B. Requicha, Aristides Univ. Rochester - New York Research on Geometric Modelling	$142
ENG-8021504 Franklin, William F. Rensselaer Polytech Inst. - New York Efficient Computer Aided Design Algorithms	$69
ECS Nudd, Graham R. Kung, Sun Yuan Nelson, John E. Hughes Research Laboratories/Univ. of Southern Calif. - Calif. VLSI Computing Structures	$200
ECS-78-25755 Director, S. W. Siewiorek, Daniel P. Carnegie-Mellon Univ. - Pennsylvania Multilevel Computer Aided Design of VLSI Digital Systems	$44
ECS Chang, Hsu Carnegie-Mellon Univ. - Pennsylvania Intelligent Bubble Storage for Robotics	$135
11 Projects Total	$955.8

ISP
Public Technology - FY 81

ISP-8017365 Abraham, R. G. Westinghouse Corp. Programmable Assembly Research Technology Transfer to Industry/Research	$455
1 Project Total	$455

MEA
Production Research - FY 81

DAR-8022667 Birk, John R. Univ. of Rhode Island - Rhode Island General Methods to Enable Robots with Vision to Acquire, Orient, and Transport Workpieces	$426.3
MEA-8018124 Hayes, Kenneth C. L.N.K. Corporation - Maryland Recogniton of Parts and Their Orientation for Automatic Handling and Inspection--Phase II	$170
DAR-8018281 Rosen, Charles A. Machine Intelligence Corp. - Calif. Microcomputer-Based Natural Language Understanding	$219.8
DAR-8023130 Nitzan, David SRI International - Calif. Machine Intelligence Research Applied to Industrial Automation	$460
DAR-8019628 McCarthy, John Binford, Thomas O. Stanford Univ. - Calif. Exploratory Research in Integrated Programmable Automation	$222.9

MEA-8114542 $124.4
Cook, George Edward
The Merrick Corp. - Tennessee
Research on Adaptive Arc Tracking for Welding

MEA-8114378 $177.6
Kerth, William J., Sr.
Taylor Systems Engineering, Inc.
Adaptive Welding System

MEA-8114761 $150
Barnard, Stephen
SRI International - Calif.
Automatic Visual Inspection of Printed Circuit Boards

MEA-8111917 $157
Boothroyd, Geoffrey
Univ. of Massachusetts - Massachusetts
Economic Applications of Assembly Robots

9 Projects Total $2,108

ESC
Automation, Bioengineering and Sensing Systems - FY 81

MCS-8106176 $25
Ruzena, Bajcsy
Univ. of Pennsylvania - Pennsylvania
Scene Understanding Via Active Sensors

ECS-8009041 $103.4
Kashyap, Rangasami L.
Purdue Univ. - Indiana
Two Dimensional Random Field Models for Images

ECS-7923893 $68.9
Sanderson, Arthur C.
Carnegie-Mellon Univ. - Pennsylvania
Signal Processing Research Utilizing a Synchronous Multi-Microprocessor Computer System

ECS-8106544 $55
Shapiro, Stephen D.
SUNY - New York
The Hough Transform: Properties, Implementation & Generalization for Image Processing

ECS-8116834 $58.5
Saridis, George
Rensselaer Polytech Inst. - New York
Advanced Intelligent Control for Trainable Manipulators

ECS-8008034 Narendra, Kumpati S. Yale Univ. - Connecticut Learning Automated Theory and Application		$114
ECS-8009825 Cannon, Robert L. Univ. of South Carolina, South Carolina Towards a Robot Sedimentary Petrographer: Determination of Algorithmic Parameters for a Microscanning System		$87.9
ECS-8106008 Ahuja, Narendra Univ. of Illinois-Urbana - Illinois Dot Pattern Processing Using Voronoi Neighborhoods		$48
ECS-8005482 Funkunaga, Keinosuck Purdue Univ. - Indiana A Program Package for Systematic Feature Evaluation with Widespread Data Application		$63.8
ECS-8105168 Wechsler, Harry M. Univ. of Minnesota - Minnesota Texture Analysis		$46.1
ECS-8012191 Gose, Earl E. Univ. of Ill., Chicago Circle - Illinois Automated Scene Analysis		$81.1
11 Projects	Total	$751.7

Mr. GORE. Well, thank you very much. We will look forward to receiving that, and thank you for your help with the hearing earlier this month.

We will next hear from NASA, represented by Lee Holcomb, the Manager of the Computer Science and Electronics part of the Office of Aeronautics and Space Technology.

Welcome, Mr. Holcomb. Please proceed.

STATEMENT OF LEE B. HOLCOMB, MANAGER, COMPUTER SCIENCE AND ELECTRONICS, OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, ACCOMPANIED BY WILLIAM B. GEVARTER, MANAGER OF ROBOTICS RESEARCH; AND RONALD LARSEN, MANAGER, AUTOMATION AND COMPUTER SCIENCE

Mr. HOLCOMB. Thank you, Mr. Chairman

Mr. Chairman and members of the subcommittee, it is a pleasure for me to appear before you today to discuss NASA's robotics technology program. I have prepared a written statement which I would like to submit for the record and I will devote my oral presentation to the major points in the written statement. NASA has been one of the pioneers in the field of robotic research. NASA's initial motivation was to enable the exploration of space in environments hostile to man. NASA has conducted and funded research in the areas of teleoperators, slave manipulators, vision systems, planning systems, and extraterrestrial roving vehicles. Major operational robotic achievements by NASA include the Surveyor lander on the Moon, which was used to evaluate the lunar surface in preparation for the Apollo mission, and the Viking/Mars lander which, under computer control, dug into the Martian soil and supplied samples to a variety of automated soil analysis equipment.

NASA's current capability for robotic operations in space, such as inspection, servicing, repair, and assembly is realized by the Canadian-built remote manipulator system, the RMS. While the RMS is an important component of our space capability, it is limited to the proximity of the Shuttle and tends to involve simple tasks utilizing vehicles with grappling fixtures.

A major technical objective of NASA's robotics technology program is to enable teleoperator systems to enhance our space operations capability. Short-term technical objectives include enabling direct human teleoperator control from the ground. Long-term technical objectives involve elevation of the human's role to supervisor of the remote system. This would be accomplished initially through task element commands and eventually job level orders.

The major robotics activity currently underway in NASA is directed toward development of teleoperator technology to augment the Space Shuttle's space operations capability. The remote orbital servicing system or ROSS concept, developed through a contract between NASA Langley Research Center and Martin Marietta, is our current focus. It is a dual manipulator system operated by a ground-based work station. Langley Research Center is developing a computerized simulation capability to perform analytical evaluations to verify system performance. Finally, the Marshall Space Flight Center is developing a "flat-floor" laboratory for systems-level integration and test, personnel training, and evaluation of human performance factors and capabilities. Flight demonstration of the space teleoperator system is targeted for the late 1980's.

The second major activity in NASA's robotics program is directed toward sensor systems. Computer vision is the most valuable sensing mode for the control of intelligent robots. The Jet Propulsion Laboratory is conducting vision research for real-time control of robotic systems in space. Real-time control requires scene interpretation and object tracking at rates of at least 15 frames per second. Performing these functions requires advances in specialized algorithms and hardware. Demonstration of such a capability is planned for 1986.

Now I would like to discuss the long-range U.S. robotic research needs. Professors John Birk and Robert Kelley, in the proceedings of their 1980 "Workshop on the Research Needed to Advance the State of Knowledge in Robotics," provide a comprehensive treatment of long-term research requirements in robotics. I would like to endorse the general findings of that workshop and identify four areas which, from a NASA perspective, deserve substantial attention. These include sensor systems, artificial intelligence techniques for planning, problem-solving, and decisionmaking, robot programing languages, and adaptive control for high-speed, structurally flexible effectors.

Intelligent robots will depend on a rich variety of information derived from sensor systems. The single most important sensing mode is vision. Research in real-time vision systems is required for a wide variety of industrial, space, and military applications. Other senses of value to robot applications include force, position, and touch. Substantial advances in each of these, particularly the integration of them into multisensor robot systems, will be required to realize intelligent robots.

A survey of robotics research supported by the U.S. Government has recently been completed as an aid to the coordination of Federal robotics research. Copies of this report have been distributed to all affected Government agencies. I am providing copies of this report, which I would like appended to my written submission.

Mr. GORE. Without objection, we will do that.

Mr. HOLCOMB. Thank you.

The role of NASA in robotics and automation includes research and development funding for efforts which: One, support agency programs; two, reduce the cost of shuttle manufacturing and agency operations; and, three, support long-term needs of U.S. industry through basic research in the area of robotics. Previous speakers before this subcommittee have articulately stated the importance of robotics and automation technology to the productivity of U.S. industry, and amplified on the aggressive steps taken by foreign countries in industrial automation. NASA endorses strong Government-sponsored programs to provide a nucleus of continuing support for long-term, high-risk but potentially high-payoff robotics and automation research to meet individual agency needs. NASA believes the investment in Government research and development in high-risk robotics and automation technology will indeed have a profound impact on the productivity of U.S. industry.

Those are my comments.

[The prepared statement of Mr. Holcomb, plus "An Overview of Artificial Intelligence and Robotics: Vol. II—Robotics," follow:]

HOLD FOR RELEASE UNTIL
PRESENTED BY WITNESS
JUNE 23, 1982

STATEMENT
of
Lee B. Holcomb
Manager, Computer Science and Electronics
Office of Aeronautics and Space Technology

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

before the

Subcommittee on Investigations and Oversight
Committee on Science and Technology
House of Representatives

Mr. Chairman and Members of the Subcommittee:

It is a pleasure for me to appear before you today to discuss NASA's robotics technology program. NASA has been one of the pioneers in the field of robotic research. NASA's initial motivation was to enable the exploration of space in environments hostile to man. NASA has conducted and funded research in teleoperators, slave manipulators, vision systems, planning systems and extraterrestrial roving vehicles. Major operational robotic achievements by NASA include the Surveyor lander on the moon, which was used to evaluate the lunar surface in preparation for the manned Apollo mission, and the Viking/Mars lander, which, under computer control, dug into the Martian soil and supplied samples to a variety of automated soil analysis equipment.

NASA's current capability for robotic operations in space such as inspection, servicing, repair and assembly is realized by the Canadian built Remote Manipulator System (RMS). While the RMS is an important component of our space capability, it is limited to the proximity of the Shuttle and tends to involve simple tasks utilizing vehicles with grappling fixtures.

NASA made important contributions to robot research through the Mars Rover Robotic Research Vehicle developed at the Jet Propulsion Laboratory (JPL) in the 1970's. This vehicle acted as a research testbed to explore robotic concepts in vision, intelligent manipulation, control and robot planning and navigation. Robotics research for the Mars Rover at JPL was supported by NASA grants and contracts to the research community at SRI International, Bolt, Beranek and Newman (BBN), Stanford University and Rensselaer

Polytechnic Institute (RPI). The work focused on NASA unique objectives but also served to stimulate generic robotic research within the United States.

During the summer of 1980, NASA held a ten week workshop to study the feasibility of using robotics and automation in future space missions. This study has helped shape the near- and far-term objectives of NASA's robotics technology program. A major technical objective is to enable teleoperator systems to enhance our space operations capabilities. Short-term technical objectives include enabling direct human teleoperator control from the ground. Long-term technical objectives involve elevation of the human's role to supervisor of the remote system. This would be accomplished initially through task element commands and eventually job level orders. The teleoperator system would evolve into an intelligent robot.

The overall funding for the NASA robotics and automation technology program is $2 million in FY 1982 with $3 million planned in FY 1983.

The major robotics activity currently underway at NASA is directed toward development of teleoperator technology to augment the Space Shuttle's space operations capability. The Remote Orbital Servicing System (ROSS) concept, developed through a contract between NASA's Langley Research Center (LaRC) and Martin Marietta, is our current focus. It is a dual manipulator system, operated by a ground-based work station. Our technology program involves research at the Jet Propulsion Laboratory (JPL) to investigate concepts for direct manned control of the system involving the integration of vision, force, and range information into the robot's control system. LaRC is developing a computerized simulation capability to perform analytical evaluations to verify system performance. Finally, Marshall Space Flight Center (MSFC) is developing a "flat-floor" laboratory for systems-level integration and test, personnel training and evaluation of human performance factors and capabilities. Flight demonstration of the space teleoperator system is targeted for the late 1980's.

The second major activity in NASA's robotics program is directed toward sensor systems. Computer vision is the most valuable sensing mode for the control of intelligent robots. JPL is conducting vision research for real-time control of robotic systems in space. Real-time control requires scene interpretation and object tracking at rates of at least 15 frames per second. Performing these functions requires advances in specialized algorithms and hardware. Demonstration of such a capability is planned for 1986.

Studies conducted at JPL and previous testimony before this Subcommittee have identified research in sensor systems as a major area requiring more basic research to support the use of robots in new industrial automation applications. While NASA's research in computer vision is directed toward space applicatons, this basic research will clearly benefit U.S. industry.

Other ongoing robotics and automation activities include research at Stanford University to develop algorithms for the precise control of structurally flexible manipulators, and fundamental investigations at JPL of artificial intelligence for robot planning and scheduling.

Professors John Birk and Robert Kelley, in the proceedings of their 1980 "Workshop on the Research Needed to Advance the State of Knowledge in Robotics," provide a comprehensive treatment of long term research requirements in robotics. I would like to endorse the general findings of that workshop, and identify four areas which, from a NASA perspective, deserve substantial attention. These include: sensor systems; artificial intelligence techniques for planning, problem solving and decision making; robot programming languages; and, adaptive control for high-speed structurally flexible effectors.

Intelligent robots will depend on a rich variety of information derived from sensor systems. The single most important sensing mode is vision. Research in real-time vision systems is required for a wide variety of industrial, space, and military applicatons. Other senses of value to robot applications include force, position, and touch. Substantial advances in each of these, particularly the integration of them into multi-sensor robot systems, will be required to realize intelligent robots.

Fundamental problems remain to be solved before a robot will be able to develop its own plans automatically. Through research at JPL, NASA has made progress in the use of expert systems to make robot planning decisions, but more work is required. Coordination of multiple effectors continues to be a challenge, as do techniques for coping with unanticipated sensor information.

Additional technological development is required in the fields of high level programming languages that can interface to existing engineering data bases in order to improve the economic viability of intelligent robots. Robots are devices which manipulate the physical world but are guided by computer programs which function in a symbolic world. Humans communicate tasks to robots in this symbolic world and have found that precise communication of intent is quite difficult.

The development of adaptive control technqiues for structurally flexible robotic systems is important to industrial automation. Appropriate control techniques must be able to integrate the information from a variety of sensors to adapt the motion of the robot to changes in its environment.

A survey of the robotics research supported by the U.S. Government has recently been completed[1] as an aid to coordination of federal robotics research. Copies of this report have been distributed to all affected government agencies. The National Science Foundation (NSF) has established an in-house robotics coordinating committee chaired by Bernard Chern, with a view toward achieving formal interagency coordination.

From NASA's perspective, U.S. industry is inclined to support development efforts which exhibit good potential for a short-term return on investment. The government should be responsible for support of long-range, high-risk research and technology development which has a high payoff potential. NASA support of robotics is designed to advance the state of the art in the field of robotics within the constraints of an appropriate federal role in research and development.

The role of NASA in robotics and automation includes research and development (R&D) funding for efforts which: (1) support agency programs; (2) reduce the cost of Shuttle manufacturing and agency operations; and, (3) support long-term needs of U.S. industry through basic research in the area of robotics.

Previous speakers before this Subcommittee have articulately stated the importance of robotics and automation technology to the productivity of U.S. industry and amplified on the aggressive steps taken by foreign countries in industrial automation.

NASA endorses strong government sponsored programs to provide a nucleus of continuing support for long-term high-risk but potentially high payoff robotics and automation research to meet individual agency needs. NASA believes the investment of government R&D in high-risk robotics and automation technology will have a profound impact on the productivity of U.S. industry.

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1 An overview of Artificial Intelligence and Robotics: Volume II - Robotics - NBSIR-82-2479, March 1982

NBSIR 82-2479

AN OVERVIEW OF ARTIFICIAL INTELLIGENCE AND ROBOTICS
VOLUME II - Robotics

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March 1982

Prepared for:
National Aeronautics and Space Administration
Headquarters
Washington, DC 20546

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Preface

This is the second volume of a two volume NBS/NASA report on an Overview of Artificial Intelligence and Robotics. This report is intended to be read by the interested technically-oriented layman, such as engineering managers, government funding officers, and others who desire an overall perspective of the field but are unable to obtain it from the highly technical and unintegrated literature in the field, or from the more flamboyant but non-technical feature articles in the popular press.

The report incorporates a summary of the basic concepts utilized in each of the many technical areas, a review of the state-of-the art, an indication of the organizations involved together with their funding sources and principal activities, research requirements, and a 5-10 year forecast of the emerging technology.

As robotics is a very rapidly changing field - with new companies, products and researchers entering the field each month - a report like this can only be regarded as an imperfect snapshot in time, and would benefit from periodic updating. Thus, quantitative information shown in this report may perhaps best be regarded as indicative rather than authoritative. Despite such shortcomings, this report should be helpful in providing a base, for organizations and individuals in and out of the government, for planning future robotic research and development, applications and utilizations.

Acknowledgments

I wish to thank the many people and organizations who have contributed to this report, both in providing information, and in reviewing the report and suggesting corrections, modifications and additions. However, the responsibility of any remaining errors or inaccuracies must remain with the author.

It is not the intent of the National Bureau of Standards to recommend or endorse any of the manufacturers or organizations named in this report, but simply to attempt to provide an overview of the robotics field. However, in a diverse and rapidly changing field such as robotics, important activities and products may not have been mentioned. Lack of such mention does not in any way imply that they are not also worthwhile. The author would appreciate having any such omissions or oversights called to his attention so that they can be considered for future reports.

AN OVERVIEW OF ROBOTICS

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ROBOTICS

I. Introduction

Robots in use today are primarily machines with manipulators that can be easily programmed to do a variety of manual tasks automatically. The robot consists of one or more manipulators (arms), end effectors (hands), a controller, power supply, and - increasingly - sensors to provide information about the environment and feedback of performance in task accomplishment. The motivation for most current robotic development is industrial: to increase productivity, reduce costs, overcome skilled labor shortages, provide flexibility in batch operations, improve product quality and to free humans from boring, repetitive tasks or operations in hostile environments.

Table 1 gives the Japanese standard classifications for industrial robots (IR's) by input information and teaching method, and relates this to the U.S. classification by control method - non-servo or servo.

As indicated in Table 2, the Japanese are the world's largest user of robots. Counting all classifications of robots the Japanese had approximately 77,000 robots in use at the end of 1980 (Yonemoto, 1981, p. 1). Table 3 presents the Japanese robotic use by industry, based on robot costs. It seems that the electrical machinery and automobile industries are the largest users of robots. Less than 1% of IR's are utilized outside of manufacturing. Table 4 presents the 1979 Japanese usage by production process. It is apparent that over 60% of the usage is for moving or positioning a workpiece. This is reflected (see Table 5) in the predominance in 1980 robot production of the fixed sequence type of robots.

Of the many reasons for installing industrial robots, the most prominent ones are to increase productivity and reduce costs. A commonly used measure for determining the ecomonics of installing robots is the payback period. This is

Table 1
Definitions and Classifications of Industrial Robots

Japanese Industrial Standard JIS B0134-1979

Manipulator	A device for handling objects as desired without touching with the hands, and it has more than two of the motional capabilities such as revolution, out-in, up-down, right-left travelling, swinging or bending, so that it can spatially transport an object by holding, adhering to, and so on.
Robot	A robot is defined as a mechanical system which has flexible motion functions analogous to the motion functions of living organisms or combines such motion functions with intelligent functions, and which acts in response to the human will. In this context, intelligent functions mean the ability to perform at least one of the following: judgment, recognition, adaptation or learning.

Classification by input information and teaching method

Manual manipulator	A manipulator that is directly operated by a man.
Sequence robot	A manipulator, the working step of which operates sequentially in compliance with preset procedures, conditions and positions.
Fixed sequence	A sequence robot as defined above, for which the preset information cannot be easily changed.
Variable sequence	A sequence robot as defined above, for which the preset information can be easily changed.
Playback robot	A manipulator that can repeat any operation after being instructed by a man.
Numerically controlled robot	A manipulator that can execute the commanded operation in compliance with the numerically loaded working information on e.g. position, sequence and conditions.
Intelligent robot	A robot that can determine its own actions through its sensing and recognitive abilities.

Source: Yonemoto, 1981, P. 5

U.S. View

INDUSTRIAL ROBOTS all have armlike projections and grippers that perform factory work customarily done by humans. The term is usually reserved for machines with some form of built-in control system and capable of stand-alone operation. But in Japan, it also includes manipulators operated by humans, either directly or remotely.

Classification by Servo Type

NON-SERVO ROBOTS

A PICK-AND-PLACE ROBOT is the simplest version accounting for about one-third of all U.S. installations. The names comes from its usual application in materials handling, picking something from one spot and placing it at another. Freedom of movement is usually limited to two or three directions in and out, left and right, and up and down. The control system is electromechanical. Prices range from $5,000 to $30,000.

A SERVO ROBOT is the most common industrial robot because it can include all robots described below. The name stems from one or more servomechanisms that enable the arm and gripper to alter direction in midair, without having to trip a mechanical switch. Five to seven directional movements are common, depending on the number of "joints," or articulations, in the robot's arm.

A PROGRAMMABLE ROBOT is a servo robot directed by a programmable controller that memorizes a sequence of arm-and-gripper movements; this routine can then be repeated perpetually. The robot is reprogrammed by leading its gripper through the new task. The price range is $25,000 to $90,000.

A COMPUTERIZED ROBOT is a servo model run by a computer. The computer controller does not have to be taught by leading the arm-gripper through a routine, new instructions can be transmitted electronically. The programming for such "smart" robots may include the ability to optimize, or improve, its work-routine instructions. Prices start at about $35,000.

A SENSORY ROBOT is a computerized robot with one or more artificial senses, usually sight or touch. Prices for early models start at about $75,000.

AN ASSEMBLY ROBOT is a computerized robot, probably a sensory model, designed specifically for assembly-line jobs. For light, batch-manufacturing applications, the arm's design may be fairly anthropomorphic.

Source: Business Week, June 9, 1980, P. 64

Table 2

IRs in Operation
(As of the End of 1979)

Japan	14,000 Units	(69%)	Total 20,268 (100%)
United States	3,255	(16%)	
West Germany	850	Western Europe 3,013 (15%)	
Sweden	600		
Italy	500		
Poland	360		
France	200		
Britain	185		
Norway	170		
U.S.S.R.	25		
Belgium	13		

(Note) Manual Manipulators and Fixed Sequence Robots are not included.

Source: Sadamoto, 1981, p. 52.

Table 3

Principle Users of Industrial Robots in Japan

	Share in 1980 (Based on Value)
Electric Machinery Industry	36%
Automobile Industry	30%
Plastic Moulding Products Industry	10%
Metal Working Industry	5%
Metal Working Machinery Industry	4%
Steelmaking, Textile, Chemical, Shipbuilding and Misc.	15%

Source: Yonemoto, 1981, p. 2

Table 4

JAPANESE ROBOT USAGE BY PRODUCTION PROCESS

Process	% of Total
Loading & Unloading	40
Transfer & Sorting	21
Palletizing	9
Welding	6
Work Maintenance	4
Assembly	3
Spraying	2
Other (Including Pouring, Screwing, Riveting, etc.)	15
Total	100

Source: Research Div., Long-Term Credit Bank of Japan, 1981, p. 28.

Table 5

JAPANESE PRODUCTION OF ROBOTS BY TYPE IN 1980

Type	Unit	Value ($ Million)
Manual Manipulators	1,940 (10%)	13 (4%)
Fixed Sequence Control Robots	13,440 (67%)	104 (31%)
Variable Sequence Control Robots	1,340 (7%)	43 (12%)
Playback Robots	2,030 (10%)	71 (21%)
NC Robots	990 (5%)	97 (29%)
Intelligent Robots	130 (1%)	10 (3%)
		Sub-Total (100%)
Other Robot-Related Devices		10
Total	19,870 (100%)	348

Source: Ogawa, 1981, p. 132.

usually given (see for example, Simons, 1980, p. 32) as the cost of the robot and accessories (including fixtures, etc.) divided by the annual savings:

$$p = \frac{I}{L-E}$$

where p = payback period in years

I = total investment

L = total annual savings in labor

E = total annual robot upkeep cost.

Typically, automation investments have required that the payback period be three years or less, with actual payback periods reaching as low as one year when multiple shifts are utilized.

II. Primitive Functions Accomplished by a Robot

Industrial robots are primarily designed for manipulation purposes. The primitive actions imposed at the hand by the manipulator are:

1. Moving
    - from point to point
    - following a desired trajectory
    - following a contoured surface
2. Changing Orientation
3. Rotation

Non-servo robots can provide a sequence of point to point (PTP) motions. For each motion, the manipulator members move full tilt until the limits of travel are reached. Thus they are often referred to as "bang-bang", "pick and place" or "limited sequence" robots. "Programming is done by setting up the desired sequence of moves and by adjusting the end stops for each axis" (Tanner, 1979, p. 7). The use of mechanical stops and limit switches yields good positional accuracy, which is typically repeatable to better than ± 0.5 mm (Simons, 1980, p. 20).

Servo-controlled robots can be designed to provide a sequence of PTP motions, with controlled intermediate velocities. They can also be used to follow a programmed trajectory or by using sensors to follow a contoured surface.

If we consider end effectors, the robot can also be made to grasp, push and pull, twist, use tools, perform insertions and assembly, and do other manipulations done by humans.

If sensors and appropriate computations are added, the robot can perceive, inspect, recognize, test and do many of the other perceptual functions now done by humans.

All applications require that the robot interact with its environment in the execution of its programmed task. Thus the robot is often designed to switch machines on and off and to accept information from machines as to their status. The robot may also have provisions for accepting signals from a moving assembly line, so it can track it. Similarly, the robot may have interface provisions for tactile, visual or other sensory inputs for feedback control.

III. Manipulator Arm Configurations

To accomplish these primitive actions, four basic configurations of manipulator arm designs have evolved:

(a) Rectangular	(Figure 1a)
(b) Cylindrical	(Figure 1b)
(c) Spherical	(Figure 1c)
(d) Anthropomorphic, articulated or jointed arm	(Figure 1d)

These arms utilize both rotary ("revolute") and linear ("prismatic") joints, as appropriate, to accomplish their function. Six degrees of freedom (6 DOF requires 6 joints) are necessary to locate the end effector (hand) at any point and orientation in the work volume. More DOF's are sometimes used to prevent interference of the arm with the work piece or other obstacles. As few as 2 or 3 DOF may suffice for a simple "pick and place" robot.

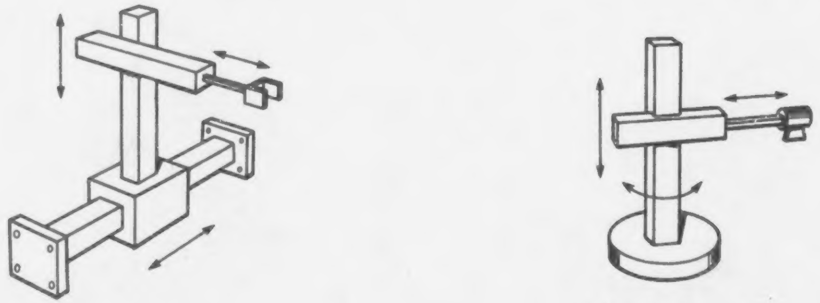
As indicated in Figure 1, only three DOF's are required to position the end effector. However for applications requiring a high degree of wrist flexibility, as many as three of the arms DOF's are located in the wrist. These DOF's are usually referred to (using aeronautical terms) as pitch, yaw and roll.

The basic four manipulator arm configurations can be combined in various ways to produce a bewildering set of manipulator combinations. These combinations can be further extended by employing angled arms and offsets. Often built-in mechanical linkages are added to do such things as constrain the motion of nominally articulated arms to cylindrical coordinates for ease of control.

In addition, the arms may be designed to be mounted on their sides, hung from the ceiling, or mounted on rails for mobility, to further multiply the range of installed configurations.

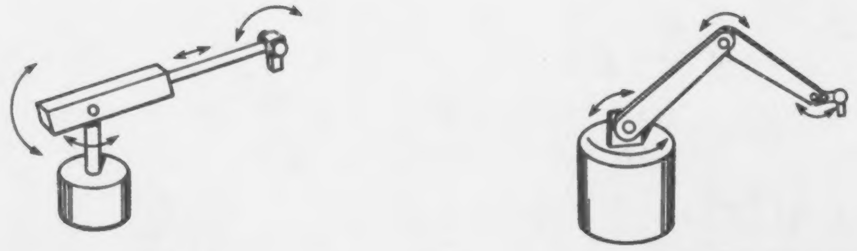
Figure 1

Basic Manipulator Geometries



Rectangular
(Cartesian Coordinates)
a.

Cylindrical Coordinates
b.



Spherical
(Polar Coordinates)
c.

Articulated or Jointed Spherical
(Revolute Coordinates)
d.

IV. Actuators

There are three major ways today of powering the actuators that move the manipulator joints: pneumatic, hydraulic and electrical. Pneumatic is simple and inexpensive but "squooshy" and is best used for "pick and place" robots whose trajectory motions are controlled by mechanical stops. Hydraulic actuation (currently the most popular system) is capable of high-power for a given size, but suffers from leakage problems as well as requiring pumps, storage tanks and other accompanying paraphenalia. Electrical-mechanical actuation is clean but doesn't offer good power to weight ratios. Stepper motors are inexpensive but sometimes lose pulses and therefore accuracy. D.C. torque motors are very reliable, offer good controllability, but can be expensive. Because the overall cost advantage of hydraulic systems diminishes with size, electrical drives are to be preferred for the small robot.

Actuators are the most problem-prone area of robotics. Thus considerable research is needed in this area to further improve reliability (robots have an approximately 98% up-time these days) and to reduce costs and weight.

V. Mobility

At present, most robots in industrial applications are fixed inplace or ride along rails, guideways or conveyors. Simple robot carts for transporting materials are now being used in industrial and commerical applications. Robot vehicles using wheels and treads have been researched by NASA for planetary exploration purposes.

Crawling robots, using their manipulator arms to grasp handholds, are being explored by NASA for use in constructing large structures in space. Walking machines are still in the experimental stage, with research going on at Ohio State University, Carnegie Mellon University (CMU), Tokyo Institute of Technology, and in the Eastern Block countries. Engelberger (1980, p. 63) states that "Practical robot devices with legs could have advantages in such applications as arctic transport, mining, agriculture, forestry, fire-fighting, explosive ordance disposal, unmanned ocean-floor surveys, and planetary exploration".

VI. End-Effectors

The hand or gripper, sometimes called the "end-effector", (attached to the robot wrist) can be a mechanical, vacuum or magnetic device for part (or object) handling or for tool manipulation. At present, most of the these interchangable devices are grippers which are simple open-and-close devices. The variety of tools and grippers that can be adapted for robot use is virtually unlimited (see for example, Engelberger, 1980, pp. 41-58). The end-effectors are usually unique to the robot application and thus customarily provided by the user, though several manufacturers offer a broad selection of devices for grasping parts that might be adaptable to the particular task being performed. Nevertheless, though hundreds of different special-purpose end-effectors now exist, the end-effector remains one of the major limiting factors in universal robot manipulation due to lack of dexterity and programmability of the hands. Extensive research and development is now underway to produce grippers that can handle a wide variety of part configurations.

VII. Control

Control of robot arms ranges from highly repeatable open loop devices to servo-controllers that utilize external sensors in the control of robot actions.

Open loop devices may be as simple as a step sequencer and positionable mechanical stops for a pick and place robot, to more complex devices using stepper motors to reproduce a desired motion.

Servo-devices can use internal sensors, such as joint position sensors, or external information sensors such as force, proximity devices, and even vision (operating under computer control).

Servos operating only on internal sensors require very careful positioning of the work-piece (which can require expensive fixturing or feeding devices).

Servos utilizing data from sensing the external environment, require more complex processing of the signal, but yield much more flexible systems.

The controller, in addition to controlling the manipulator motion, often also serves as an interface to the outside world - coordinating the robots motions with machines and assembly lines and turning on and off machines that it is operating.

A. Pick and Place Robots

The simplest controllers are non-servo (open loop) devices that rely on sequencersand mechanical stops to control the manipulator end-point positions along each of the axes. These "limited sequence" robots are also referred to as "pick and place," "bang-bang," or "fixed stop" robots. These robots have no provision for trajectory control between the end points.

B. Programmable Robots

Programmable robots are servo controlled robots of two basic types: "point-to-point" and "continuous path."

Point-to-point robots are directed by a programmable controller that memorizes a sequence of arm and end-effector positions. Hundreds of points may be memorized. The robot moves in a series of steps from one memorized point to another under servo control using internal joint sensors for feedback. Because of the servos, trajectory control between the memorized points is possible and relatively smooth motions can be achieved.

Continuous path robots do not depend on a series of intermediate points to generate a trajectory, but duplicate during the playback process the continuous motions recorded during the teaching process. Thus, these robots are used for painting, arc welding and other processes requiring smooth continuous motions.

C. Computerized Robots

Computer-controlled robots are capable of being programmed "off-line" using a high level programming language and do not have to rely on being physically taught.

D. Sensory Robots

These are computerized robots that interface to the outside world thru external sensing such as sight or touch. These "intelligent robots" are capable of adapting to a variety of conditions by changing their actions based on relating the sensed information to their goals or preprogrammed decision points.

E. Robots as Part of a Flexible Manufacturing System

A flexible manufacturing system (FMS) is a programmable batch-processing arrangement that contains programmable machine tools and transfer devices all under central computer control. When robots are used in such a system, the robot controller may itself be just the bottom layer of a hierarchical control system for the FMS (c.f. Topperwein, et al., 1980, pp. 96-105, or Albus, 1981A, pp. 261-280).

VIII. Sensor-Controlled Robots

Sensor-controlled robots are the first step on the path to truly intelligent robots - robots that can determine their own actions based on their perception and planning abilities.

The simplest versions of sensor-controlled robots utilize contact switching for stopping the arms and for opening and closing grippers. More sophisticated robots are now beginning to use touch, force and torque sensing. Forces and torques can be derived from stress measurements or from internal signals (e.g. derived from back EMF). Tactile information may be derived from deflection-induced resistance variations of a special sensing surface, or by various other ingenious approaches.

Work in France and at MIT on "artificial skins" with embedded arrays of touch sensors, opens the possibility of a robot eventually being able to determine position, orientation and identity of parts by touch alone. This may be particularly important for difficult assembly operations (Kinnucan, 1981). Proximity and range sensing are also now being considered.

Vision, the most complex of all the sensory modalities, is now beginning to find its way into robotic control.

IX. Robot Vision

In the industrial manufacturing arena, to circumvent the problem of requiring that the workpiece be in a prescribed position and orientation (pose) for the robot to operate upon it, sensory systems are now beginning to be employed. Vision provides perhaps the most flexible approach to avoid all the fixturing that would be required to achieve a fixed pose.

Figure 2 lists the desired functions of a machine vision system to achieve fully flexible sensor-controlled manipulation. Figure 3 indicates potential applications for such a system.

A. Methods for determination of pose:

1. Range can be determined in four principle ways:
    - Stereo
    - Triangulation
    - Active ranging (e.g. time of flight of light or sound)
    - Using optical focusing.
2. Orientation can be determined by:
    - Observing the relationship of three (or more) known object points that are not all colinear in the viewing field, provided that the relative ranges connecting these points are known.
    - Deriving surface normals using the intrinsic image concept (Barrow and Tennenbaum, 1981).
    - Deducing it based upon the response of lighting on the object, utilizing known characteristics of the object. (This is simplified if structured lighting such as sheets of light are employed).
    - Interferometry measuring the phase differences of an oscillating signal received at multiple points.

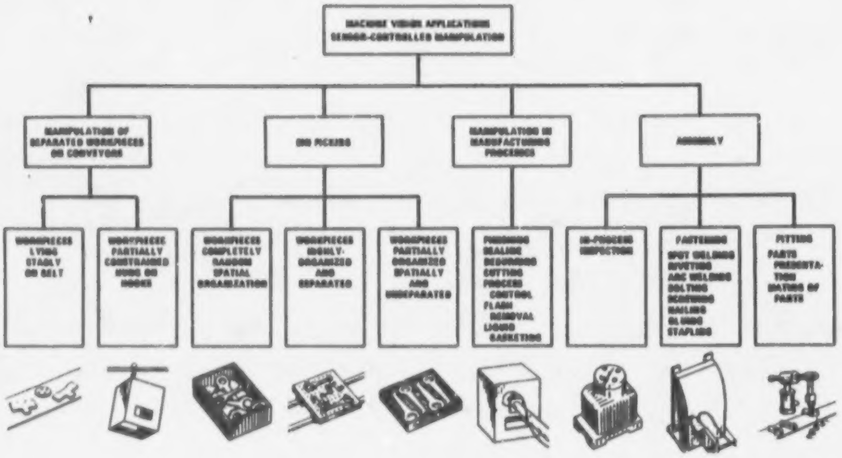
Figure 2

Desired Functions of Machine Vision for Sensor-Controlled Manipulation in Industrial Manufacturing

- Recognition of workpieces/assemblies and/or recognition of the stable state where necessary.
- Determination of the position and orientation of workpieces/assemblies relative to a prescribed set of coordinate axes.
- Extraction and location of salient features of a workpiece/assembly to establish a spatial reference for visual servoing.
- In-process inspection -- verification that a process has been or is being satisfactorily completed.

Source: Rosen, 1978.

Figure 3
Block Diagram of Potential Vision Applications in Robotics


MACHINE VISION APPLICATIONS
SENSOR-CONTROLLED MANIPULATION
MANIPULATION OF SEPARATED WORKPIECES ON CONVEYORS
BIN PICKING
MANIPULATION IN MANUFACTURING PROCESSES
ASSEMBLY
WORKPIECES LYING STABLY ON BELT
WORKPIECE PARTIALLY CONSTRAINED HUNG ON HOOKS
WORKPIECES COMPLETELY RANDOM SPATIAL ORGANIZATION
WORKPIECES HIGHLY ORGANIZED AND SEPARATED
WORKPIECES PARTIALLY ORGANIZED SPATIALLY AND UNSEPARATED
FINISHING SEALING DEBURRING CUTTING PROCESS CONTROL FLASH REMOVAL LIQUID GASKETING
IN-PROCESS INSPECTION
FASTENING SPOT WELDING RIVETING ARC WELDING BOLTING SCREWING NAILING GLUING STAPLING
FITTING PARTS PRESENTATION MATING OF PARTS

Source: Rosen, 1978, p5, (Illustrated Version Shown is From Saveriano, 1980, p15, and is Used by Permission of Robotics Age).

B. Feature Extraction

Though it is possible to operate directly on an analog output of a vidicon imager (by such approaches as optical correlation, or template matching), it is now fashionable to use solid state imaging arrays, such as CCD or CID devices, which directly provide points (pixels) in the image.

These pixels are then digitized by intensity levels (usually 2 to 16) so as to be put in a convenient form for operation upon by a computer. From this data, edges and regions are determined. Edges are considered to occur when there is an intensity gradient exceeding a selected threshold. These gradients are derived from intensity differences between adjacent pixels (often using an averaging scheme to reduce noise effects). Regions are grown by annexing ("clustering") adjacent pixels that are close to the same intensity level. Various schemes (heuristics) exist to connect lines having gaps, smooth irregularities, and remove discontinuities in regions (all resulting from noise in the image). The result (which can be considered as a form of data compression) is a reduced image that consists of edges and regions. Further data compression might be achieved by representing edges by sets of straight or curved lines (the ends and curvature of which are all that need to be known).

C. Object Recognition

Having determined edges and regions, it is possible using the methods of Section A to determine position and orientation. However, often it is necessary to determine which object is being observed from a collection of possible objects. This may be accomplished by

1. Template Matching: Using a stored image in the computer.
2. Use of Edge and Region Statistics: This may be curvature of edges, area moments of inertia, ratio of square of perimeter to area, number and/or location of holes or notches, etc.

3. Fourier Transform: Determining the coefficients of the spatial Fourier transform and comparing them to the coefficients of known objects.

D. Future Techniques

In the future we may see:

- Greater use of direct range measurements - e.g. scanning laser radar, or LED's and photo diodes using phase or intensity measurements.
- Parallel processing to obtain feature extraction in real-time.
- Improved methods for determining edges and regions.
- Use of optical markings for recognition, for optical code reading or for determination of pose.
- Use of intrinsic image analysis - to determine surface orientation, depth, relationship of foreground to background, and texture.
- Scene analysis for less-structured situations.

X. Programming a Robot

There are four primary methods for programming a robot:

- Physical-setup, in which the operator sets up programs by physically fixing stops, setting switches, arraying wires, etc. This is characteristic of the simpler robots.
- Lead-through, in which the operator leads the robot through the desired positions and locations by means of a remote teach box. (These points are recorded and used to generate the robot trajectory during operation.)
- Walk-through, where the robot arm is physically manipulated through the desired motions (which are recorded and then played back by the robot-control during operation).
- Writing a software program, which is then executed when desired.

The emphasis in programming research today is on software programming of computer-controlled robots. Work on sensor-controlled manipulation is extending the scope for programmability. Interacting with the robot by means of software, provides more flexibility then the other programming methods, and allows for conditional actions or flexible adaptations. Various high level robot programming languages such as VAL (Unimation) and AML (IBM) are now beginning to become available to aid in the software generation.

Simons (1980, p. 107) notes that software programs can be divided into two types: "In explicit programming, the user requires explicit instructions for every action the robot must take. In world modelling, the robot is more autonomous and can make decisions according to its knowledge. World-modelling systems, largely in the research stage, tend to require a considerable amount of computer power but are able to carry out complex tasks. The most important world-modelling languages are AL, AUTOPASS, and LANA..."

XI. Kinematics and Dynamics

A. Coordinate Transformations

If the arm is programmed by walking-thru, then it is simply necessary to record the simultaneous joint positions during the walk-thru. If the arm is led-thru, then in more sophisticated systems, that can operate in tool point, world, or other coordinate systems, it is necessary to do the needed coordinate transformations for each joint in order to obtain the desired end-effector orientation and position. This is particularly true when the arm is being programmed by writing software.

When the arm is controlled via feedback from a vision or other sensor, it is necessary to do coordinate transformations to convert the camera or hand coordinates to base or computer coordinates. For vision (or other sensor) control, the sensor interpretation and coordinate transformations need to be done in real time. As the mathematics for exact transformations requires time-consuming calculations, approximate simplifications have been developed to speed the calculations. In some systems, individual microprocessors are used to process the kinematics at each joint.

Note that arms are often designed so that the wrist motions are mechanically constrained to cylindrical or rectilinear coordinates to simplify control and reduce coordinate transformation requirements.

B. Trajectory Selection

For moving the end effector from one position (or point) to another, various schemes are possible for choosing the motions for moving the joints. Approaches for articulated arms include:

- Variations from preprogrammed paths.
- The "dominant axis" approach: some joints may be allowed to adapt while others follow fixed movements.

- All joint motions move proportionately relative to the slowest joint, so that all joint motions terminate at the same time.

Considerations of this sort become particularly important for off-line or real-time programming of computer-controlled robots.

C. Dynamics

At present, all robot arms are made relatively stiff so that structural flexibility is minimized (to promote repeatability). However, this requires stiff and usually heavy arms with high power actuators, lowered carrying capacity, and reduced speed. Research is now underway on the control of structurally flexible arms to help overcome these limitations, and in active control to control flexure for achieving on-line precision under load as during assembly or drilling operations. The 15 meter long Romote Manipulator System (RMS) for the Space Shuttle is probably the most extreme case of a structurally flexible manipulator thus far.

XII. Research Requirements

A. Different Views

In considering research requirements it is very helpful to differentiate between near-term needs and far-term needs. Figure 4 indicates the near-term needs for improvement in IR's, as perceived by Japanese users. Note the emphasis is on robot flexibility and versatility of movement, speed, and ease of programming.

In observing how private enterprise is responding to the IR user desires, Umentani (1981, p. 81) indicates that the robot manufacturers most important targets for development include:

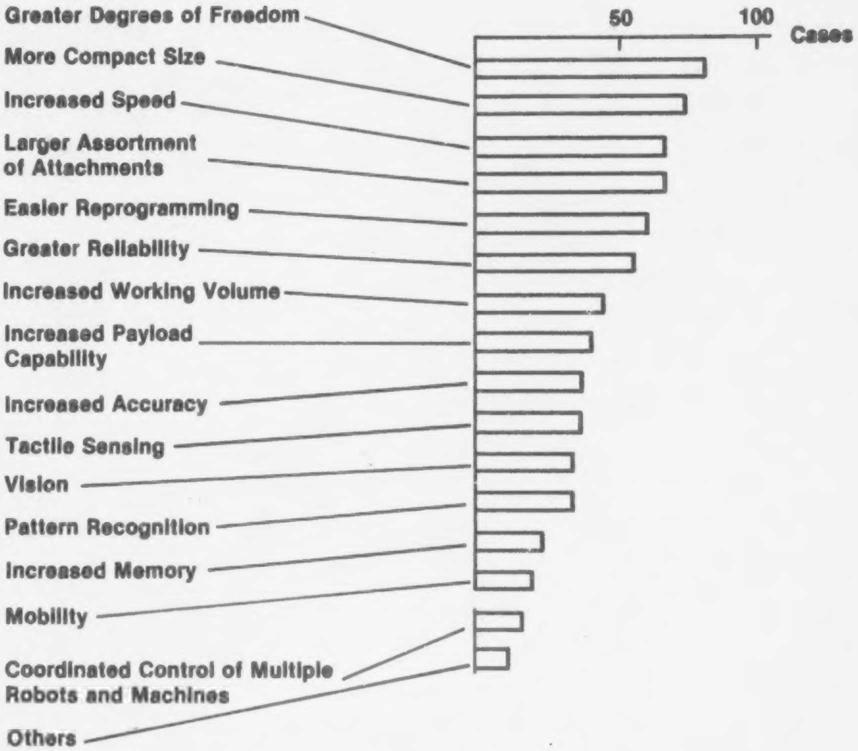
- reduced production costs
- smaller installation space requirements
- greater flexibility
- larger carrying capacities
- modular robots components to enable a building block approach to diversification of functions
- visual and tactile feedback and recognition systems

Table 6 lists the main research subjects being pursued by Japanese Robot Manufacturers. These may be regarded as relatively near-term. Note the correspondence with user desires in their emphasis on speed, flexibility and programming versatility.

As we move towards the longer term, we encounter robot research such as is being pursued in Japanese Universities and Japanese Government

Figure 4

1980 JIRA User Survey of Desired Improvements in Industrial Robots



Source: Umentani, 1981, p. 84.

Table 6

Main Research Subjects In IRs
1980 JIRA Survey of Japanese Robot Manufacturers

Order of Importance	Subject	No. of Research Subjects	% of Total
1	Increased Speed	49	13.1
2	More Compact Size	36	9.7
3	Computer Control	32	8.6
4	Lighter Weight	30	8.0
5	Interchangeability by Module	25	6.7
6	Object Recognition	19	5.0
7	Increased Payload	17	4.6
8	Improved Actuators	14	3.8
9	Self Diagnosis	14	3.8
10	Adaptive Control	14	3.8

Source: Umentani, 1981, p. 98.

Research Institutes. Here a 1980 JIRA research survey indicates (see Umentani, 1981, pp. 95-96) that their primary research topics (in decreasing order by number of research projects) are:

- control
- locomotion
- vision
- tactile sensing
- manipulators
- end effectors
- programming methods and tools

Figure 5 lists the desirable goals for future robots (from a U.S. vantage point) as seen by Engelberger (1980). He states (p. 125) that of the missing robotic attributes, the two most cruical ones are vision and tactile sensing. As indicated in Figure 6, this view is shared by the particpants in the NBS/RIA Robotics Research Workshop.

Kelley and Huston (1980), Birk and Kelley (1981), and Albus (1981B) have also attempted to come up with research requirements for future robots, though they did not attempt to prioritize them. Their requirements are summarized in Figure 7. In the following discussion we will combine these research needs into categories for ease of presentation.

Figure 5

Desirable Goals for Future Robots

1. Rudimentary sense of vision to provide
    a) recognition data
    b) orientation data
2. Tactile sensing to provide
    a) recognition data
    b) orientation data
    c) physical interaction data
3. Computer interpretation of the visual and tactile data
4. Multiple appendage hand-to-hand coordination
5. Computer directed appendage trajectories
6. Mobility
7. Minimized spatial intrusion
8. Energy conserving musculature
9. General purpose hands
10. Man-robot voice communication
11. Total self diagnostic fault tracing
12. Inherent safety (Asimov's Laws of Robotics)
13. All the capabilities above available for a price which allows purchase and operation within the traditionally accepted rules for economic justification of any new equipment

Source: Engelberger, 1980, p. 118.

Figure 6

Recommended Distribution of U.S. Robotics Research Funds/Effort

	%
Binary Vision	14
Gray Scale Vision	12
Off-line Programming	12
Control Systems	11
Touch, Force, Torque Sensing	11
End Effectors	10
Integration Into CAM Systems	8
Mechanical Systems	7
Simulation and Modeling	6
Safety	4
Mobility/Line Tracking	4
Others	1
	100%

Source: NBS/RIA Robotics Research Workshop, 1979, p. 49.

Figure 7

Basic Research Needs in Robotics (not prioritized)

Kelley and Huston (1980)

Manipulator Kinematics
Control
Locomotion
Sensing
Artificial Intelligence
Higher-Order Languages
Smaller Actuators

Albus (1981B)

Accuracy
Speed and Dexterity
Sensing
Control
Knowledge Representation
Programming (Higher Order Languages)
Standardized Interfaces (Modularity)
Mobility

Birk and Kelley (1981)

1. Intelligence
   - Knowledge Representation
   - Auto. Prob. Solving, Decision Making, Planning
2. Control
   - Flexible Structures Control
   - Modeling
   - Real-time Sensory Control
   - Fault Tolerance, Monitoring and Repair
3. Actuation
4. Manipulation and Hands
   - Performance Evaluation
   - Kinematic Planning for Assembly
   - Speed
5. Dexterity
6. Locomotion
7. Sensing
   - Vision
   - Tactile
   - Real-time Computation
8. Programming
9. Adapation and Learning

B. Synthesis of Needed Research

1. Manipulator and Actuator Design:

To achieve the higher speeds, flexibility, accuracy, efficiency and dexterity that is desired in future robots, additional research in manipulator arms are needed. For large manipulators and precision work, joint and arm structural flexibilities can be a problem. Therefore stiff, but lightweight arms are desirable to minimize this problem and to aid in increasing speed. However as variable compliance in different directions is often desirable to provide the "give" needed for inserting parts and other assembly operations, unique design approaches may be required.

At present, actuators are one of the more problem-prone areas of robots. In addition, actuator efficiencies are in the order of one tenth that of human musculature. Smaller, more reliable and efficient actuators and drive mechanisms, with high load to weight ratios, are needed for the high speed, lighter weight robots of the future.

For greater dexterity and less intrusion into the work-zone, it is also necessary to understand the mutual interdependence of end effector and manipulator kinematics. Also research on micro-manipulators is needed for applications to micro-electronics and biology.

A unified theory is needed on how to design an arm for smooth universal movements, satisfaction of functional requirements, and to provide the required load capacities throughout its motion spectrum. A standardized approach to performance measurement and evaluation is required to enable comparison of robots not only in such factors as working volume, load capacity and reliability, but also in aspects such as speed, smoothness and accuracy throughout their operating range..

To help determine manipulator accuracy (now a limiting factor in off-line programming of open-loop manipulator operations), a universal stochastic model of mechanical errors of manipulators needs to be devised.

2. End Effectors

Umetani (1981, p. 110) states that "the most difficult barrier in industrial robot design... is the design of dexterity in hands and fingers." Thus, much work is needed to devise designs for general purpose hands (and the means to control them), such that the whole arm need not move to provide the desired dexterity. Because general purpose hands are not yet available, multiple end effectors may be required for a single application. This in turn requires some type of quick change wrist design.

3. Control

Kelley and Huston (1980) indicate that further research is needed on the basic robot problem: given the desired external or absolute displacement, velocity and acceleration of the hand, determine the optimal physical and internal motion parameters. (Birk and Kelley, 1981) state that procedures have been recently developed for efficiently obtaining and solving governing dynamic equations for robotic systems with flexible links and joints. However, optimizing the arm motion still presents problems of convergence and uniqueness (Kelley and Huston, 1980).

Though the repeatibility of arm positioning via open-loop (no external sensory feedback) robot control has been good, accuracy for initially positioning the arm via open-loop control has been poor. In addition, no efficient means of robot calibration has yet been determined. Thus it is important that more work be done on improving open-loop control accuracy. Accuracy degradation due to flexure can be a particularly troublesome problem when trying to perform precision operations under load, such as drilling without the aid of jigs.

An important area of control not yet solved is control of structurally flexible manipulators. This problem, important to high speed manipulation with manipulators having high load to weight ratios, may require real-time simultaneous management of a large number of command and control variables. An associated problem with such manipulators may be the large changes in moments of inertia as the manipulator is extended and a load applied. Another problem associated with high speed manipulation, requiring additional research, is the generation of time-optimal trajectories.

An area for which little is known about ideal solutions, is the control of redundant-axis manipulators used to provide additional manuever capability.

Design of control systems for fault tolerance will become particularly important as robots become more autonomous.

Finally, lack of suitable strategies for control of multi-fingered hands is still one of the principle factors retarding design of dexterous hands.

4. Sensory-Controlled Manipulation

One of the most desirable features for improving robot flexibility is sensory capability. Vision, the most popular U.S. robot research area, appears to be the most desirable sense for present and future IR's. Next in importance is touch.

To take full advantage of sophisticated sensory data, real-time control using sensors is needed. Hierarchical control may be the appropriate means to handle such data, though control logic systems such as pattern reference feedback logic may be appropriate in certain contexts.

In addition to vision and tactile sensing, dynamic control using force feedback is an important area of research. Also of increasing importance as robots become more autonomous, is proximity sensing as used before final contact and to avoid obstacles. Other sensors will increasingly have roles in inspection and in determining the type of material being observed. Research is needed in the use of models in sensory processing and interpretation.

It is also necessary to explore the tradeoff between the use of sensors and imposing more structure on the robot environment. As sensory control is perfected, the tradeoff will undoubtedly shift towards the direction of using sensors.

5. Vision

Vision becomes more important as the environment becomes less structured. Therefore vision is needed more for fire-fighting, household servants, robot explorers, etc., than for IR's. Vision can also reduce manipulator accuracy requirements, by making real-time adjustments practical.

At the current state of the art, additional research in recognition and geometric representation is needed. As greater capability is desired, three dimensional vision combined with world models and spatial reasoning will become important. Current

3-D research in vision systems center on the use of range-finding, structured light, and binocular vision systems. Further-out, research is required in the analysis of image sequences (optical flow: shape from motion), intrinsic image analysis (determining shape from a single image by disambiguating the response to light), and improved methods to recognize objects in clutter. The bin-picking problem is a classic one in this latter area.

One of the most important research areas in vision is approaches to improve the speed of visual processing. This includes research in computational elements structured for visual processing, which includes parallel-processing CPU's, and special chips for edge-finding, Fourier analysis, etc.

6. Tactile and Force Sensing

What is needed is better use of contact sensing data. This includes better resolution in touch and force sensing. An important result could be the ability to recognize parts and to determine their relative position and orientation through such methods.

7. Programming a Robot

Programming by teaching is not practical for small lot production, particularly when sensory interaction is involved. Thus, improved techniques are needed for generating robot control data. These could include high-level programming languages, software debugging tools, world models, and the ability to directly utilize CAD data bases and sensory inputs. Robot simulation tools can aid in off-line programming. Also needed are better geometric modeling systems. As robot usage advances, it would be desirable to produce aids for writing programs to orchestrate multiple arms and multiple sensors, and for systems with distributed control.

8. Intelligence

Plantier and Bodmer et al. (1981, p. 63) assert, "Artificial Intelligence is the technological area which needs most to be developed and mastered to accelerate robot evolution." Birk and Kelley (1981) indicate that an intelligent robot is one capable of:

- receiving communication
- understanding its environment by the use of models
- formulating plans
- executing plans
- monitoring its operation

Thus research in all these areas is important.

Communication: Use of a natural language interface, or computer graphics or even voice commands would all be helpful in simplifying communication with a robot. In addition, intelligent aids for robot users to help plan and develop robot usage are also needed.

Knowledge Representation: A key ingredient in advanced robotics is knowledge representation. However, the tradeoff between control algorithm complexity and representation complexity needs to be explored. Sophisticated internal models of the environment are needed to generate expectations, to interpret sensory data, and for use in automatic generation of robot control data (such as for real-time decision-making).

Representations are also needed to enable qualitative reasoning about physics and space for use in planning and problem solving.

Parallel processing will be needed to make real-time modeling a reality.

Planning: Automatic problem-solving or planning is one of the keys to future intelligent robots. Planning is even needed for acquiring information from sensors. Needed is research on ways to use large amounts of domain-specific knowledge to guide planning and responses to recognized situations.

One of the difficult, but important areas of research needed is in developing plans that deal with time.

For certain tasks, the software for handling contingences is becoming excessive. Thus means for automatic monitoring and correction are needed. In addition, plan-monitoring and repair is also in need of research. It would also be useful to be able to store successful plans in categories so that they can be reused. In general, it is desirable that the system be capable of adaptation and learning.

Automatic assembly in non-highly structured environments is a key research area. Development of kinematic strategies for assembly is needed. Assembly could be aided by model-based generation of programs that use local sensory information in assembly tasks. Research is also needed for planning and orchestrating the actions of cooperating robot systems for assembly and other purposes.

Intelligent controls can be thought of as coupling control theoretic approaches with advanced AI methodolgies. To advance this area, better understanding of modular hierarchical structures is needed as well as how to generate hierarchical plans associated with such structures.

To make intelligent robots really useful, it is necessary to develop methods that will enable them to function in real-time (not having to pause for computation) with realistic computers.

9. Robot Mobility

For industrial robots tending machines, furnaces, etc., the robots are often in use only a fraction of the time, the remainder being in a wait mode. To make better use of the robots, machines are frequently arranged so that one robot can tend several machines. Sometimes this involves moving the robot (motion along tracks being the usual means). Locomotion is needed to further extend the working range and for use in hazardous environments and in remote locations. In many cases, a truly mobile robot would be preferred that can be used where needed. Mobile robots would be particularly advantageous in environments less structured than that found in factories, such as in the construction of ships, buildings and roads, in mining, and in undersea or space use.

New mechanical mechanisms, other than wheels, are needed for mobility over uneven terrain. However, mobility systems tend to amplify compliance and vibration problems (which can be minimized by careful design and the use of sensor-driven control). Active suspensions are needed for uneven terrains, climbing, etc. For legged vehicles, the key problems are stability, control and optimal motion synthesis. In walking machines very little is known about the stability of various gaits. Advances are needed in the hierarchical control of multi-body systems. Efficient algorithms need to be developed for solving the governing dynamic equations.

If the mobile robot is to be supervisory-controlled, then optimal partitioning of the task between the operator and machine becomes an important research area.

10. Modularity

Further work is needed not only to develop modular manipulators, but also to enable integrated modular systems that can consist of a variety of robots, tools, sensors and computers all connected together. To do this, standardized interfaces are needed. It will be necessary to partition the control problem into modular components and to develop interface standards for communication between these components. An important goal is to be able to write an off-line program for one robot and be able to use it with a differently designed robot.

The 1980 NBS/Air Force ICAM Workshop on Robot Interfaces (1981) considered the following items for standardization.

- simple sensor interface between simple peripheral devices and a robot control system.

- Wrist interface between the robot wrist and the end effector.
- Complex sensor interface that covers vision, complex touch and other such sensors.
- Common robot control interface, providing robot independent trajectory descriptions.
- Robot Programming Languages
- Integration of robots into robot systems for automated manufacturing.

It was concluded that both the simple sensor and wrist interfaces were ready for standardization, but that it was too early in the development of the other areas to begin a standards effort at that time.

XIII. Commercially Available Robots and Components

Engelberger (1980, p. 117) indicates that many of the attributes required to make industrial robots practical in an industrial environment are available today. These (see Figure 8) include good positioning repeatability, reliability, flexibility, easy programmability and adequate load capacity, all at a affordable price.

The rapid growth of industrial robots (roughly 35% per year) and the entry of new manufacturers and new products makes its inappropriate to try to list or even summarize all the robots currently available. However, the following are good sources of information to keep current with available robot products:

- Robotics Age, a bimonthly magazine popularizing robots, P.O. Box 725, La Canada, CA 91011.
- Robotics Industry Directory published yearly by Robotics Age, P.O. Box 725, La Canda, CA 91011. This directory lists complete information on over one hundred different models of currently available robots, robot components and peripherals. It also provides information on robot distributors, robot research institutes and consultants in the robot field. Robot Systems and Products, providing a monthly new products update, is also available from Robotics Age.
- Specifications and Applications of Industrial Robots in Japan published by Japan Industrial Robot Association (JIRA), 3-5-8, Shiba Koen, Minato-ku, Tokyo, Japan. A 1982 edition is currently available. JIRA is a good source for all information on Japanese robots.
- Robotics Today, a quarterly magazine on industrial robotics published by the Society of Manufacturing Engineers in cooperation with the Robot Institute of America, One SME Drive, P.O. Box 930, Dearborn, MI 48128.

Figure 8

Robot Attributes Now Commercially Available

1. Work space command with six infinitely controllable articulations between the robot base and its hand extremity
2. Teach and playback facilities - realizing fast, instinctive programming
3. Local and library memories of any practical size desired
4. Random program selection possible by external stimuli
5. Positioning accuracy repeatable to within 0.3 mm
6. Weight handling capability up to 150 kilos
7. Point-to-point control and continuous path control, possibly intermixed in one robot
8. Synchronization with moving workpieces
9. Interface allowing compatibility with a computer
10. Palletizing and depalletizing capability
11. High reliability -- with not less than 400 hours MTBF
12. All the capabilities available for a price which allows purchase and operation within the traditionally accepted rules for economic justification of any new equipment

Source: Engelberger, 1980, p. 117.

- The Industrial Robot, a quarterly magazine with a European orientation toward industrial robots, published by IFS Ltd., 35-39 High St., Bedford MK42 7BT, England.

An excellent recent guide to industrial robots for perspective users - Sanderson, R. J. et al., Industrial Robots: A Summary and Forecast for Manufacturing Managers, 1982 - can be purchased from TECH TRAN Corp., 134 N. Washington St., Naperville, IL 60540.

In addition, various robotic newsletters (such as "Robot News International," also available from IFS Ltd., "Industrial Robots International," available from Technical Insights, Inc., P.O. Box 1304, Ft. Lee, N.J. 07024; and the "Robotics Newsletter," available from Bache, 100 Gold St., New York, NY 10038) offering information on new robot products and investments have recently begun to appear. Datamation, Byte, Business Week, Time and other technical and popular magazines have also recently begun to have feature articles on robotics.

At the end of 1981, there were some 50 U.S. based firms marketing or preparing to market robots (Conigliaro, 1981), the leaders being:

- Unimation Inc. (projected to have 32% of the estimate $215 million (3075 units) U.S. market in 1982) and Cincinnati Milacron (projected to have 25% of the U.S. market in 1982).

Several of the large U.S. auto, electrical and computer firms have been building robots for internal use and are now entering or considering entering the commerical robot market.

Japan at the end of 1981 had over 130 different manufacturers producing robots, many for their own internal use. Table 7 presents the robot production by major Japanese manufacturers for the years 1980 and 1981. Of the estimates by JIRA of 19,400 robots, valued at 77 billion yen, produced in Japan in 1980, only 3% were exported.

In 1979, approximately 2400 robots were sold in Europe. European manufacturers having a major share of this market include:

ASEA - Sweden

Olivetti - Italy

The Eastern Block Communist countries have been moving in the direction of robots to make up for their serious labor shortages. Business Week (Aug. 17, 1981) reported that the Soviets plan to manufacture 40,000 robots by 1985 to counter not only the shortage of skilled labor, but also absenteeism associated with drinking.

Table 7

Number of Robots Produced by Major Japanese Robot Manufacturers

Note: The figures in brackets indicate approximate value.

Company	1980 Achievement	1981 Target	Major Product Function
Kawasaki Heavy Industries	450 ($22 M)	650 ($31 M)	Spot welding Arc-welding
Yaskawa Electric	360 ($16 M)	630 ($29 M)	Arc-welding
Hitachi	150	480 ($22 M)	Spot welding Arc-welding
Mitsubishi Heavy Industries	120	240	Spot welding Print-spraying
Kobe Steel	120 ($7 M)	200 ($13 M)	Arc-welding Paint-spraying
Star Seiki	-	($13 M)	Plastic mould picking
Shinmeiwa Industry	360 ($4 M)	480 ($9 M)	Arc-welding
Fuji Electric	130	200 ($9 M)	Inspection
Fujitsu-Fanuc	480 ($4 M)	600 ($7 M)	Machine processing Assembling
Sankyo Seiki	-	300 ($4 M)	Assembly
Nitto Seiko	-	120 ($3 M)	Assembly

Source: August 1981 Survey (Survey Japan, 1981, pp. 210-211).

XIV. Commercially Available Vision Systems for Robots

Present commercially available vision systems for use with robots are basically devices that generate and analyze 2D images. These systems recognize objects by their silhouettes. Principle current manufacturers of sophisticated computer vision systems are:

Machine Intelligence Corporation (M.I.C.)
Sunnyvale, CA

Automatix Inc.
Burlington, MA

Octek Inc.
Burlington, MA

M.I.C. Vision Module

This Vision Module is based upon prototype software and hardware developed at SRI under NSF and industrial affiliate support (see Gleason and Agin, 1979).

The Vision Module consists of a solid-state TV camera, a preprocessor interface and a LSI-11 microcomputer. The vision software, stored in the LSI-11 memory, includes the entire library of vision subroutines previously developed at SRI, several application programs (such as training-by-showing and execution of part recognition), as well as newly developed capabilities. The capability to develop application programs by calling the vision-library subroutines makes the Vision Module a general-purpose vision system. The Vision Module is intended for a variety of industrial vision applications such as inprocess inspection, sensor-controlled manipulation, and visual servoing.

The Vision Module can recognize parts on the basis of their size and shape regardless of their position or orientation. The part (lying in one of its stable states previously used to train the module) is recognized on the basis of a set of shape descriptions, including area, perimeter, number of holes, length of major and minor bounding ellipse axes, first and second moments of area, etc., and various algebraic combinations of these.

The Vision Module operates by appropriately thresholding the image in the preprocessor to achieve binary silhouettes of the objects in the scene. A frame buffer stores the binary image (consisting of zeros and ones) to achieve timing independence between the camera and the controlling microcomputer. Each line is sequentially scanned and "run-length" encoded (i.e., edge points recorded where the pixels change from zero to one or vice versa). Each run-length segment on a line is matched against segments of the previous line to determine their overlapping relations hips. Using these relation ships, the program traces the appearance and disappearance of blobs (regions) as the image is processed from top to bottom. Only one line at a time of image data needs to be stored in the computer.

At the heart of the vision processing are connectivity analysis routines which segment the image into contiguous regions (called "blobs") even in the presence of noise. During the connectivity analysis, sequences of perimeter points are extracted. Using this blob boundary information, other desired parameters such as area, area moments, shape, position and orientation of the blob can be computed.

The system is trained by showing the object to the TV camera resulting in all potentially useful shape descriptions being automatically calculated and stored. Then the same object is moved and photographed several times and the mean and variance of these descriptors calculated and stored. This resulting set of means and variances, can be used as a "prototype" for that object or class of objects. New objects can then be recognized in either of two ways. One, by using a normalized nearest-neighbor method, where the best fit of the features of the new object to the set of prototypes is selected. Two, using a binary decision tree (which can be built by the Vision Module software upon command) recognition is done by measuring one feature at a time, and at each stage subdividing the recognition problem into two smaller problems until a single choice remains. The time to read in, process and implement recognition is in the order of one second.

Complete vision systems cost from $30-40 thousand dollars. M.I.C. also markets the VS-110 Machine Vision System version for real time inspection tasks.

M.I.C. which is currently rapidly expanding, is placing increased emphasis on turnkey systems, and improved man-machine interfaces. The problems of resolution speed and cost are also being vigorously attacked.

The Automatix Autovision System

The Autovision System (Rheinhold and Vanderbrug, 1980) also uses the SRI algorithms as its main base for vision processing and in many ways is similar to the MIC system. However, the Autovision System's preprocessor (Scheinman, 1981) has a pixel memory capable of storing several images at once, or several bits of grey level information, or any combination. The versatility of the system comes from the system's powerful AI-32 control processor, which with its 32 bit internal design and megabyte memory address space, can operate in parallel with the preprocessor and has the ability to interface with multiple preprocessors and various other input and output devices. The control processor operates under an Automatix developed operating system. Most of the system software is factory programmed in PASCAL, except where speed or compactness is so critical that assembly language is used.

The primary interface for the user is via the Automatix application language, RAIL, which is designed for the non-computer oriented user. This powerful and flexible robot programming language makes it possible to sequence the operations of the Autovision system so that the desired task can be performed.

Octek Vision System

Octek has several vision systems based on a circuit board developed in 1980. It can handle two high resolution solid state TV cameras with 320 x 480 pixel arrays. The system has an on-board microprocessor that can manipulate images at four frames per second. The system can handle a 16 gray level scale.

There are four memory planes so that similarities and differences between images can be determined. The system relies on a Data General or DEC computer for computation. The basic circuit board costs about $4500, with the cost of a complete vision system ranging from $16,000 to $40,000.

KEYSIGHT AND CONSIGHT

At General Motors, several different computer vision systems are now operational (Rossol, 1981). KEYSIGHT is an example of a system for inspection tasks in automobile manufacturing. It uses a low-resolution solid state camera to inspect for the presence or absence of valve spring cap keys on automobile engines. Ingeniously applying fairly standard computer vision algorithms for edge finding, etc., the system locates the center of the valve spring assembly and then, based on the keys being brighter than the holes they fit over, determines if the keys are present.

More interesting is CONSIGHT, an example of a robot vision system that uses structured light to detect the silhouette of passing objects. Using a robot arm, CONSIGHT transfers a moving stream of non-touching, randomly oriented parts from a moving conveyor belt to a predetermined location.

Structured light provides a means to deal with situations that require both high spatial resolution and fast response. It allows part geometry to be sensed directly, as opposed to being inferred through grey level picture processing.

CONSIGHT is logically partioned into independent vision, robot and monitor subsystems. When the vision subsystem has seen the entire object, it sends to the monitor the object's position and belt position reference value. The robot subsystem then executes a previously "taught" robot program to transfer the part from the belt to a fixed position.

A single narrow and intense line from two parallel, separated sources is projected across the belt surface perpendicular to the belt's direction of motion. A linear array camera builds a conventional two dimensional silhouette imate of passing parts by collecting a sequence of these image strips. For each object detected, a small number of numerical descriptions is automatically extracted for part classification and position determination.

CONSIGHT is now commercially available, having been licenced to Unimation, Cincinnati Milacron, M.I.C. and Automatix.

XV. Current Robot Research

In Japan

Robot related research in Japan can be placed into three categories - research done by universities and research institutions, by industry, and by special government sponsored task forces. A 1980 JIRA survey found that a total of 88 research projects were then underway at universities and public and private research institutions. However unlike the U.S., there were no large-scale research efforts at the universities or technology colleges.

Areas of emphasis in research projects at Japanese universities and research institutions are (Hasegawa, 1981, pp. 162-163):

- increasing robot speed
- coordination of multiple arms
- dexterous robot hands with tactile recognition capability for automatic assembly
- sensory development for intelligent robots
- robot locomotion
- robot control and application software development

In the United States

Robot research in the U.S. is primarily aimed in the direction of making robots more intelligent and versatile, with vision research being given a high priority. Albus (1981B, p. 7) states, "Much remains to be done in sensor technology to improve the performance, reliability and cost effectiveness of all types of sensory transducers. Even more remains to be done in improving the speed and sophistication of sensory processing algorithms and special purpose hardware for recognizing features and analyzing patterns in space and time."

Robotic research efforts at U.S. universities (roughly reflecting FY-82 funding) are indicated in Table 8. Note that the research is centered on greater

Table 8A

Robotics Research

Institution: Stanford University

Principal
Researchers: Thomas O. Binford, Bernard Roth,
Robert Cannon, Larry Leifer
(23 Grad Students, 4 PostDocs)

Research Funding: Approx. $1,400 K/year from NSF, ARPA
and NASA

Manipulation

- Control of flexible manipulators
- Control of multiple manipulators
- Design of three-fingered hand

Perception

- Robot Vision
- Stereo Mapping
- Special purpose VLSI for vision
- Segmentation
- Force sensing and control

Programming and Intelligence

- AL (arm language) one of the most advanced robot programming languages available today.
- ACRONYM system for geometric modeling and reasoning for model-based vision and for programming robots.
- Work on CAD, resulting in a simulator for mechanical systems and robot arms, and for off-line programming.

Mobility

- A continuing program of navigation and perception.

Table 8B-1

Institution: Artificial Intelligence Lab., M.I.T.

Research Funding: $1.75M DARPA and ONR.

I. Robotics Mechanisms and Control

Principal Researchers: Hollerback, Seering, Mason, Pubrick, Salisbury, Asada, Lorenzo Perez, Brooks, Hillis,

Manipulation

Design of Dexterous Hands

- Tendon-actuated three-fingered hands (for use with PUMA) lighter, nimbler, more compliant.
- Controllers for tendon-actuated fingers and shoulders.

Manipulator Design

- Direct drive actuation
- Developed a recursive Lagragian formulation of the dynamics of manipulators.
- Developed a simulation for robot linkages and biological arms.
- Hybrid controller that allows the available degrees of freedom to be divided into position servoing and force feedback servoing as needed to achieve the compliance required for assembly and operation under load.

Perception

Force and tactile sensors for automating compliant assembly task.

- High resolution tactile sensor.
- Strain gage force sensor.

Programming and Intelligence

Developing a high level language based on a geometric modeling system developed at the AI Lab.

- Allows errors to be modeled, as well as keeping track of spatial relationships in ways programmers find natural.

- Connecting a PUMA directly to a LISP machine to be able to program it in this geometric modeling language - to improve robot speed, accuracy and interfacing with sensors and effectors.

II. Robot Vision for Parts Assembly and Repair

Principal Researchers: Brady, Grimson, Horn, Larson, Nishihara, and Poggio.

Perception

Acquire possibly overlapping laminar workpieces off a textured background.

- Real time edge detection carried out in hardware using a camera developed at M.I.T.
- M.I.T. constructed frame grabber provides a interface to commercially available area array cameras for real time processing of image files.

Utilize 3D vision for guiding the acquisition of objects from a bin of parts.

- Photometric stereo to determine local surface orientation.
  (1) Using multiple light sources and assuming Lambertian reflectance.
  (2) Use of diffuse light sources to determine layout of scences containing specular objects.
- Binocular stereo vision utilizing matching of detected edges to obtain depth.

Table 8B-2

Institution: Mechanical Engineering Dept., M.I.T.

Principal Researchers: Thomas B. Sheridan, Nam P. Suh, Nathaniel H. Cook,
Neville Hogan, (10 grad. students)

Research Funding: Approximately $500K/Yr. from NOAA, ONR, NSF and NIHR.

I. Use of Robotics (Teleoperators) Underseas

Manipulation

Teleoperators under computer control.

Perception

Tactile sensing for oceanbottom operations.

Measurement arm attached to base of robot to subtract out base motion.

Vision tradeoffs of video frame rate, resolution and number of gray scale levels.

II. Upper Extremity Prosthetics

- movement control
- adaptive control stiffness

Table 8C

INSTITUTION: Robotics Institute, Carnegie-Mellon University

DIRECTOR: Raj Reddy

RESEARCHERS:
15 Faculty
6 Research Associates
18 Graduate Students
23 Staff

RESEARCH FUNDING: Approx. $4 M/year from Westinghouse, Digital Equipment Corp, ONR, DARPA, NSF, and other industrial sponsors.

Manipulation

- Direct drive rare-earth magnet electric actuators for manipulator joints
- Multi-processor control systems
- Dexterous end effectors for handling compliant parts

Perception

- Laser range sensor
- Proximity sensors
- Binary and gray scale image analysis and understanding
- Touch, force, pressure, vibration, temperature, and chemical sensors
- 3D sensors

Mobility

- Mobile cart
- Gait and legged motion analysis

Manufacturing

- Factory of the Future Project
    - integrated factory system
    - research testbed for manufacturing problem
- Intelligent Factory Management System
    - Job-shop planning and scheduling
    - Factory modelling and analysis
    - Flexible user interfaces
- Flexible machining
    - multiple robot and machine integration and control
- Flexible Assembly
    - multiple robot and sensor integration and control
    - multiple processor controllers
    - electronic assembly

Programming and Intelligence

- Knowledge representation
- Problem-solving techniques for planning and scheduling

Table 8D

Institution: Rhode Island University

Principal
Researchers: John Birk
Robert Kelley

Research Funding: Approx. $200 K/yr. from NSF
Approx. $1 M/yr. from Industrial Associates

Manipulation

- Dexterous end effectors
- Articulated hands (includes manipulation within the hand itself).
- Design methods for hands

Perception

- Visual Pose estimation
- Touch sensing

Programming and Intelligence

- Robot programming language

Manufacturing

- Successfully demonstrated bin-picking
- General methods to enable robots with vision to acquire, orient and transport workpieces
- Design of production systems utilizing robots

Table 8E

Institution: University of Florida

Principal
Researcher: Del Tesar (+10 faculty from 5 disciplines and 20 grad. students)

Research
Funding: Approx. $1 M/yr. from DOE, NSF and State of Florida

Manipulation

- Human augmentation with real-time digital computer assistance (computer-based teleoperators)
- Robot geometry, kinematics and dynamics - to achieve high-level dexterity
- Control of structurally flexible manipulators
- On-line robot precision under load (for batch processing)
- Actuator modules - to enable construction of customized manipulators

Programming and Intelligence

- Hierarchical control in an unstructured environment - using force feedback assistance.

Table 8F

Robot Research at Other Universities

University	$ Yearly Funding	Manipulation, Perception, Mobility	Programming and Intelligence	Manufacturing
Purdue	100K NSF	• Robot Vision	• Robot Control System • Robot Programming Languages	• Modeling of parts flow thru in industrial plants
U. of Mass	300K NSF			• Design of parts for automatic assembly • Economic application of assembly robots
U. of Mich	500K State of MI	• To Implement a new Robot Lab		
U. of MD		• Robot Vision		
U. of Rochester	200K NSF,ONR	• Machine Vision	• Computer graphics language - PADL	• Automated Manufacturing
U. of Arizona	100K	• Teleoperators		
Ohio State (Robert McGhee)	1M NSF & DARPA	• Legged locomotion	• Manipulator Dynamics and Controls	
U. of IL U. of PA U. of WA U. of Texas R.P.I.		• Small projects in robotics and related work		

dexterity, improved sensory perception, higher-order robot programming languages, increased robot intelligence, and computerized manufacturing and assembly. As indicated in Table 9, the focus of robotics research in the U.S. non-profit research laboratories is on manufacturing, with emphasis on computerized planning, factory management, assembly and inspection.

Table 10 indicates robotic research efforts in commercial U.S. companies. The emphasis is on manufacturing, assembly and computer vision for part recognition and inspection.

Information on research and development in some of the U.S. companies specializing in sophisticated computer vision is indicated in Table 11. The emphasis is on vision for inspection and robot control, and on simplified command capability.

Table 12 gives an indication of the research activities of the principle U.S. robot manufacturers. Emphasis is on advanced control systems, improved programming techniques and mechanical design.

Though there is no central focus for robotics in the U.S. Government, several government agencies are involved in robotics research and a number of others are looking into applications.

Table 13 (roughly reflecting FY-82 funding) provides an overview of robotics research performed within the U.S. Government. In general, these activities can be viewed as exploratory research into robotic applications.

Table 14 presents an overview of robotics research (roughly reflecting FY-82 funding) supported by the U.S. Government. NSF primarily supports basic research, ONR supports a mixture of basic and applied research, while the V.A. is focussed on potential applications for the handicapped.

Table 15 (again roughly reflecting FY-82 funding) indicates some of the government supported robotics applications development in the manufacturing and rework areas.

The various U.S. military services are considering future robotic research efforts that could lead to replacing humans, or leveraging their capabilities, for dangerous jobs or missions and for increased productivity.

It is estimated that the current (FY-82) overall U.S. Government support for robotics research and development is approximately 18 million dollars per year.

Research in Europe and the Soviet Union

The Western Europeons are estimated to be spending two to four times as much as the U.S. on robotics and related research. (A recent survey of teleoperator and robotics research in Europe indicates that $10 million per year is being spent in telemanipulation R&D alone, (Plantier and Bodmer et al., 1981, p. 8).) As in the U.S., the emphasis is on making robots more intelligent and versatile. "Germany, Italy, Sweden, France, Switzerland and the United Kingdom, either in national research laboratories or in robot manufacturers, are presently the most advanced European countries in computer vision and sensor-based robots" (Plantier and Bodmer et al., 1981, p. 12).

No figures are available on robotic research in the U.S.S.R. and the Eastern Block Countries, but they appear to be making a strong effort in robotics in order to improve productivity and overcome labor shortages. However, the Soviets lack of ready access to digital and computer circuitry is hindering their research effects in advanced robots (Teschler, 1981, p. 48).

Table 9A

Robotics Research

Non-Profit Lab: Charles Stark Draper Lab, Inc.

Principle
Researchers: Jim Nevins
Dan Whitney

Research Funding: Approx. $1 M/yr. from NSF and Industry

Manufacturing

- Part-mating science for assembly operations
  - Sensory feedback
  - Adaptive learning
  - Passive compliance
  - Models of assembly process
- Economic and configuration modeling for making choices among competing technologies in designing industrial systems
- Flexible assembly system design
- Operational strategies
- Product design for producibility

Applications, with industry, range from precision products with low annual volume to products with annual volumes in excess of several million. Techniques developed are also applicable to other environments, such as space, underwater, and medical.

Table 9B

Robotics Research

Non-Profit Lab:	SRI International
Principal Researcher:	David Nitzan
Research Funding:	Approx. $1 M/yr. from NSF and Industrial Affiliates

Perception

- Machine vision for inspection and recognition
- Robot vision involving structured light, a combination of binary and gray-scale vision, and local features to distinguish overlapping parts

Manufacturing

- Vision-guided arc-welding
- Printed circuit board inspection
- Programmable assembly

Table 10

Robot Research in Commercial U.S. Companies

Company	Research Activities
GM Warren, MI	• Robot vision systems for inspection and part transfer (KEYSIGHT, CONSIGHT)
	• Automatic small parts assembly
GE Schenectady, NY	• Flexible computer-controlled high-speed precise assembly, to handle different versions of a one product family from a data base
	• Evaluation of existing robots for use in GE manufacturing
Westinghouse Pittsburg, PA	• Robotics Research Laboratory evaluating use of commercial robots
	• Supports productivity research at CMU ($1M/yr.)
	• Adaptable Programmable Assembly System (APAS) ($1M/yr), cost-shared with NSF
	• Supports Research on Teleoperators for Nuclear Power Plants at U. of Florida
IBM	• Developed own robots for its manufacturing operations
	• Developed robot programming languages - AUTOPASS and EMILY
Texas Instruments	• Developed own robot for assembly and testing of hand calculators
Martin Marrietta Denver, CO ($3M/yr.)	• Robotics research directed at DOD and NASA interests - Autonomous devices - Automated diagnosis/checkout - Speed requirements of space manipulators - Simplified high-speed coordinate transformations - CAD robot program planning system
	• Two arm coordinated manipulation (for DOE)

Table 11

Near-Term R&D in Sophisticated Computer Vision Systems

Automatix Burlington, MA	• Robot Vision • Robot Microcomputer Control Systems • Robot Programming Language (RAIL) • Commercial Robot Applications - arc welding
Machine Intelligence Corp. Sunnyvale, CA	• Computer Vision Systems for Turnkey Inspection • Materials Handling and Assembly Systems • Univision System developed in cooperation with Unimation for the PUMA robot - programmed in VAL robot language. This is the first commerically-available seeing robot. • Research in person/robot communication for non-computer oriented people.

Table 12

Research Activities of U.S. Robot Manufacturers

Unimation

- Advanced control systems
- Calibration techniques
- Programming techniques
- Mobility systems
- UNIKA™ vision for arc welding

Cincinnati Milacron

- New control system architectures
- Programming language
- Mechanical design

Other Robot Manufacturers

- Similar activities - all aggressively developing new and improved product lines.

Table 13

In-House Government Robotic Research

Organization	Research Activities

National Bureau of Standards
$1-1/2 M/yr.
	Standards
	• Robot Interface Standands
	• Robot Performance Measures
	• Programming Language Standards for
	  - robot systems
	  - integrated computer-aided manufacturing
	Advanced Concepts for
	• sensory-interactive control systems
	• modular distributed systems
	• sensor interfaces to the control systems of robots and machine tools
	• vision systems
	Focussed Application
	• Automated Manufacturing Research Facility
	  - planning
	  - scheduling
	  - routing
	  - inspection
	  - demonstration of a completely automated machine shop consisting of computer controlled NC machines served by robots and robot carts, producing mixed configurations of parts on demand

Table 13 (cont.)

In-House Government Robotics Research

Organization	Center	Activity
NASA $1M/yr. 12 man years	Langley Research Center Hampton, VA	• Robotics Laboratory to develop teleoperated and automated spacecraft servicing techniques - Trajectory planning and multi-arm coordination - Man-machine interface for remote systems - Operating system for concurrent processes in a distributed computer network - Robotics simulation
	Marshall Space Flight Center Huntsville, Ala.	• Research on end-effectors • Man-machine interface for teleoperation
	JPL Pasadina, CA	• Research in Hand-Eye Coordination • Control of structurally-flexible manipulators • Teleoperators • 3 fingered hand with Stanford U.
Naval Ocean Systems Center San Diego, CA $650K		Exploring application of robot and teleoperator systems • submersibles • land vehicles • underwater manipulators • stereo optic and acoustic vision • remote presence • autonomous robots - knowledge representation and automatic decision-making • complex robot systems specification and verification

Table 13 (cont.)

In-House Government Robotics Research

Naval Ocean Systems Center Hawaii $300K	Exploring the use of telepresence (teleoperation with sensory feedback directly to the operator, giving a sense of being at the work site) for use in materials handling aboard ship.

Table 14

U.S. Government Supported Robotic Research

Organization: NSF
Washington, D.C.

Program (FY-81)	Organizations Supported and P.I.	Activity
Production Research $2M (W. Spurgeon) (Emphasis on robotics for assembly)	U. of R.I. - Birk	Part acquisition using vision
	C. N. K. Corp. - Hayes	Part Recognition
	SRI - Barnard	Auto. Visual PCB inspection
	SRI - Nitzan	M.I. applied to Industrial Auto.
	Merrick Corp. - Cook	Adaptive arc welding
	Taylor Sys. Engr. - Kerth	Adaptive arc welding
	Stanford U. - McCarthy & Binford	Integrated Programmable Auto.
	M.I. Corp. - Rosen	Natural Language
	U. of Mass. - Boothroyd	Economic applications
Mechanical Systems (A. Strauss) $700K (Emphasis on control, dynamics, kinematics, and design)	U.C. Berkeley - Tomizuka	Digital Control of Industrial Process
	" - Dornfield	Control of arc welding
	UCLA - Dubowsky	Dynamics of high speed machines
	U of FL - Sandor	Kinematic analysis
	" - Hole	Nonlinear dynamic structual synthesis
	U. of Nebraska - Schade	Mechanism motions
	Rutgers - Lee	Design of high speed mechanisms
	Stevens - Tricano	Optimum design of mechanisms.
	Columbia - Freudenstein	Forces in high speed linkages
	Ohio State - Srinivasan	Control of machine tool feeds
	U. of Conn. - Huston	Multi-body dynamics

Program (FY-81)	Organizations Supported and P.I.	Activity
Automation, Bio-engineering and Sensing Systems $750K (Emphasis on robotics vision and intelligent controls) (N. Caplan)	U. of PA - Rozina	Scene understanding
	Purdue - Kashyap	Image modeling
	CMU - Sanderson	Parallel signal processing
	SUNY - Shapiro	Edge detection in images
	U. of S. Carolina - Cannon	Auto signal processing
	U. of IL - Ahuja	Dot pattern processing
	Purdue - Funkunaga	Image feature evaluation
	U. of Minn. - Wechsler	Texture analysis
	U. of IL - Gose	Auto. scene analysis
	RPI - Saridis	Intelligent controls
	Yale - Narendra	Self-learning systems

Table 14 (cont.)

U.S. Government Supported Robotic Research

Organization: NSF
Washington, D.C.

Program (FY-81)	Organizations Supported and P.I.		Activity
Public Technology (A. Schwarzkopf) $450K	Westinghouse	- Abraham	Programmable assembly
Computer Engineering (B. Chern) $300K	U. of Rochester	- Voelcker & Requicha	Geometric modeling
	CMU	- Chang	Robot memory
Intelligent Systems (Y. T. Chien) $100K	VPI	- Shapiro & Haralick	Geometric reasoning
	U. of PA	- Bajczy	Scene understanding using active sensing

Table 14

U.S. Government Supported Robotic Research (cont.)

Organization	Organization Supported	Activities
Office of Naval Research Arlington, VA $1.7M/yr. (Marvin Denicoff)	M.I.T. $700K/yr.	• Fundamental research in - vision - manipulation - reasoning
	CMU $700K	• Autonomous Unmanned Underwater Vehicles
	SRI $250K	• Communication and negotiation among distributed robots
	U. of Rochester $100K	• Machine Vision
Defense Advanced Research Projects Agency Arlington, VA (Robert Kahn) $300K/Yr.	M.I.T. $300K	• Fundamental research in robotic vision, manipulation and reasoning (in cooperation with ONR)
Veterans Administration Washington, D.C. (Dr. Margaret Gianni) $400K/yr.	Applied Physics Lab John Hopkins Univ. $100K	• Robotic work station for quadriplegics
	Rehabilitation Engr. Center Stanford Univ. $200K	• Robotic aids for severely disabled individuals • Supervisory voice and head-orientation command of a PUMA robot • Human/Machine Interface
	VA Hospital - West Roxbury $50K	• Myographic wheelchair control
	VA Hospital - White River Junction, N.H. $65K	• Communication control aid

Table 14 (cont.)

Organization	Program	Organizations Supported & P.I.	Activity
A.F.O.S.R. (A.F. Off. of Scientific Research) Bolling AFB, D.C.	Manufacturing Science (Tom Walsh) $2 M/yr.	Developing Educational Research centers of excellence	• Assembly in manufacturing

Table 15

U.S. Government Robotic Applications Development

Organization	Activity
Naval Air Rework Facility San Diego, CA $3 M/yr.	• Development of robots to - remove rivets and fasteners from airplane wings - strip and repaint aircraft - perform wing assembly
Air Force Materials Lab. Wright Patterson AFB Dayton, Ohio $1M/yr.	• Robotic applications in manufacturing (Part of ICAM)
U.S. Army Human Engr. Lab. Aberdeen Proving Grounds, MD	• Formulating a plan for military applications of robotics
Office of Manufacturing Technology DARCOM	• Robot applications in manufacturing

XVI. Applications Now and in the Future

Figure 9 indicates current and anticipated future use of robots in manufacture in Japan. Currently, machine tool processing is dominant, followed by welding, assembly, and plastic molding. In % of value, assembly, and measurement and inspection are expected to increase while spot welding, plastic molding and machining processes are expected to decrease.

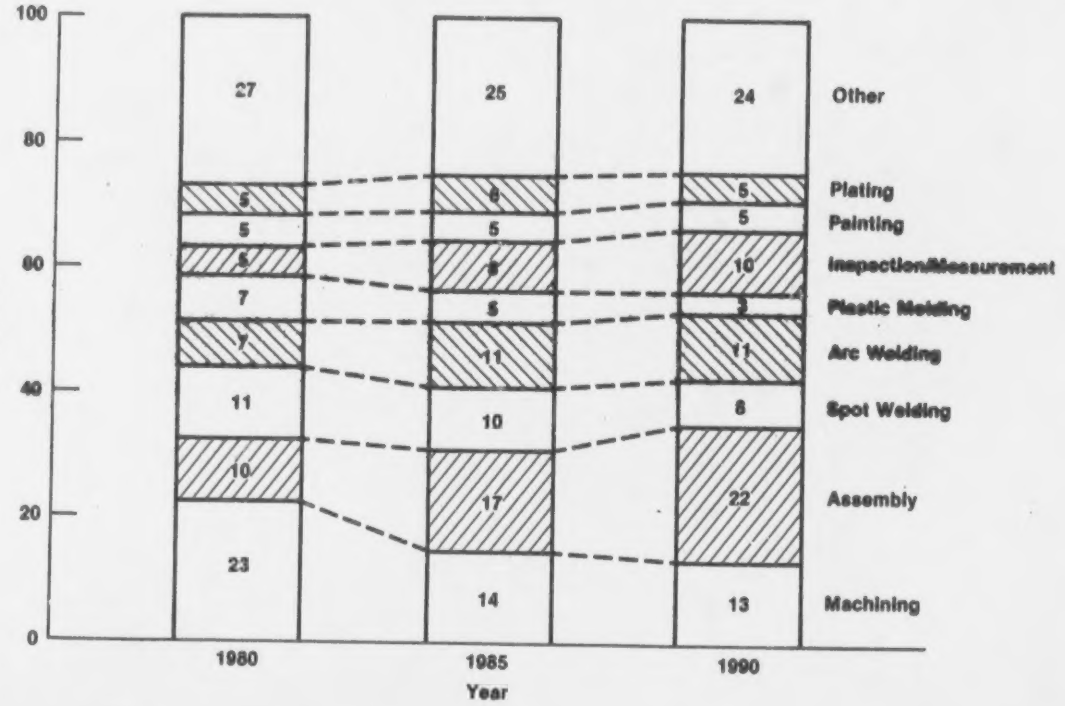
Table 16 indicates current and 1990 estimates of major uses for industrial robots in the U.S. In general the same trends are visible in the U.S. as in Japan, with welding and materials handling being currently dominant, moving towards assembly being the dominant application in 1990.

A recent JIRA forecast of robot applications development, introduction and diffusion is shown in Figure 10. Observe that by 1985 it is anticipated that robots for assembly, inspection, reactor maintenance, cleaning and ocean development, as well as all phases of manufacturing, will be in commercial use, with diffusion relatively complete by 1990. In the last half of this decade it is forecast that construction and mining robots, robots for fire fighting and even robots to assemble soft goods like textiles will begin commercial diffusion. In the same time period, prosthetic arms and legs, and robots for use in patient care and other medical applications will become widespread.

In the late 1980's, robots for use in various military applications, such as use in dangerous missions and hostile environments are also expected to appear. Also in the late 80's, robots for use in servicing of space satellites are anticipated. In the 1990's, robots for use in the construction and assembly of large space structures and in space manufacturing are forecast. Starting around 1995, semi-autonomous robots are foreseen for use on extra terrestrial surfaces for exploration, mining, materials processing, manufacture, and the construction, tending and maintaining of space installations.

Figure 9

JIRA Forecast of Japanese User Needs for IR's by Production Process



Source: Research Div. of the Long-Term Credit Bank of Japan, 1981, p. 74.

Table 16

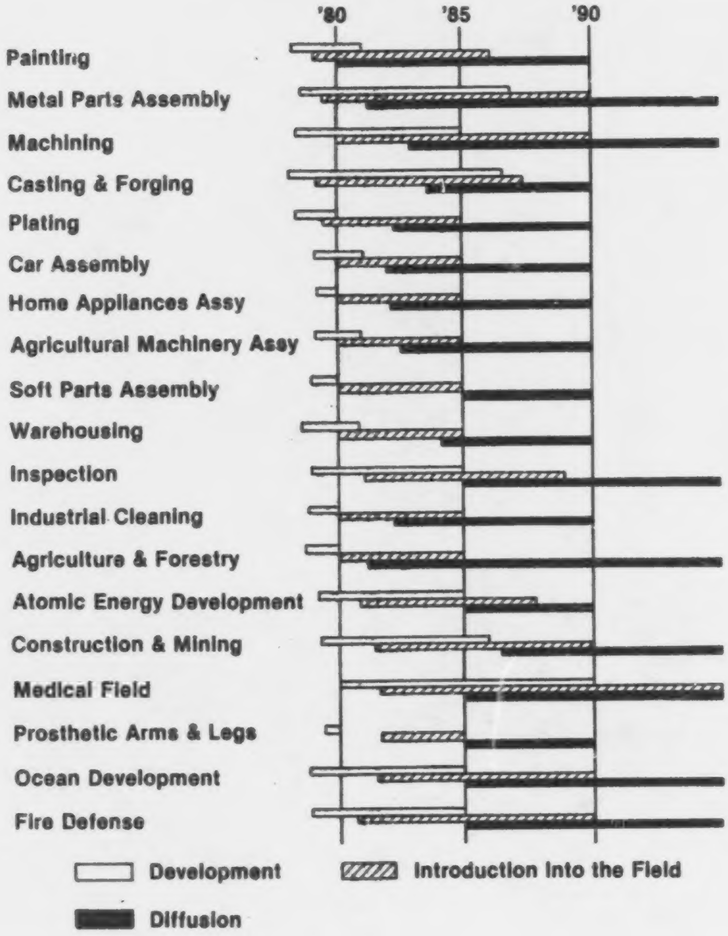
Estimated U.S. Robot Order Trends By Usage

	Through 1981	1990
Materials handling, including machine loading and unloading	25-30%	30-35%
Assembly	10%	35-40%
Spot-Welding	35-45%	3-5%
Arc-Welding	5-8%	15-20%
Paint spraying	8-12%	5%
Other	8-10%	7-10%

Source: (Conigliaro, 1981, p. 6)

Figure 10

Robot Development, Introduction and Diffusion



Source: JIRA (Hasegawa, 1981, p.171)

The general trend is toward robots with ever increasing intelligence and sensory capabilities. Engelberger (1980, p. 135) suggests that robots will eventually be entering the service industries, with such diverse applications as garbage collection and fast food preparation and dispensing. He even suggests that "...a [limited] household robot may be practicable before the end of the 1980's decade."

XVII. The Expanding Robot Population

Table 2 presents JIRA's (The Long-Term Credit Bank of Japan, 1981, p. 52) estimate of the world's robot population as of the end of 1979. The figures shown are for high-quality robots and exclude manually manipulated robots (teleoperators) and fixed sequence robots. Note that Japan with 14,000 robots has nearly 70% of the world's total, compared with 16% (representing a little over 3,000 units) for the U.S.

Figure 11 projects the U.S. robotics industry growth through 1990, when it is estimated that the U.S. will have roughly 100,000 IR's in operation, or some 30 times that of 1979. This estimate is predicated on major diversified companies - such as GE, Westinghouse, GM and IBM - entering the market as now appears to be happening.

Table 17 presents JIRA's forecast for the production of IR's in Japan through 1990, while Figure 12 indicates how this production will be distributed.

Integrating the results from Tables 2 and 17 and Figure 11, Figure 13 presents the composite forecast of the industrial robot population through 1990. It appears that the world's robot population will pass 1,000,000 in the early 1990's, and will therefore have a major impact on the world's productivity.

A recent article in Business Week (Dec. 14, 1981) indicates that the robot pace is continuing to accelerate and even the figures quoted here may be very conservative.

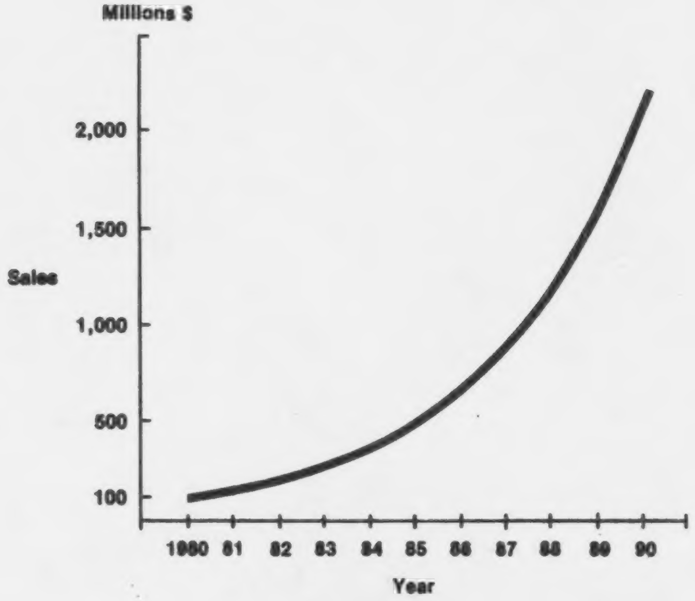


Figure 11

U.S. Robotics Industry Growth
1980-1990

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Estimated Sales ($ Millions)	$ 100	150	215	280	395	540	725	875	1125	1520	2070
Estimated Units Sold	1450	2100	3075	4000	5600	7715	10350	13000	17000	23000	31350

(Assumed Avg. Robot Cost Approx. $70K Each)

Compound Growth of Revenue Per Year: 35%

Source: Congliaro , 1981

Table 17

Forecast of Aggregate Demand in Manufacturing for All Classes of IRs in Japan

(Unit $ Billion)

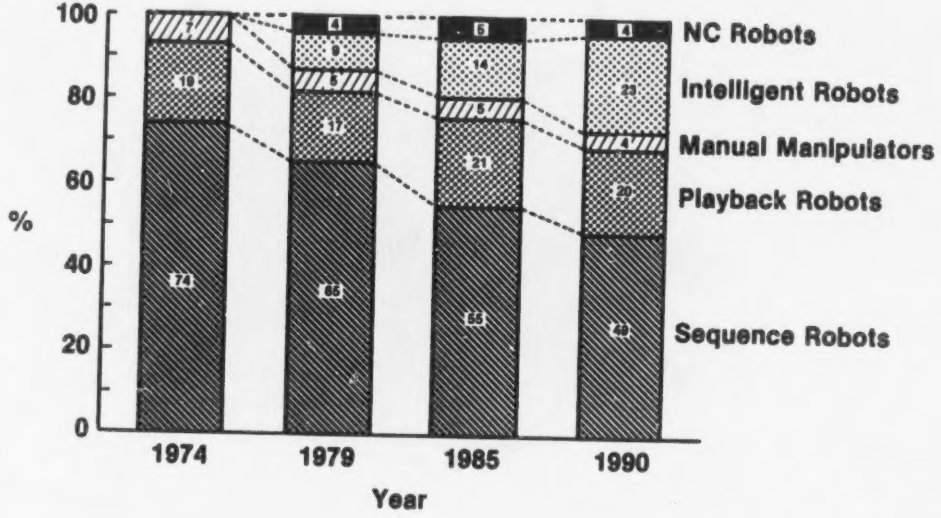
	1980	1985	1990	Annual Growth Rate 1985/1980	Annual Growth Rate 1990/1985
Domestic Demand	0.3	0.8 to 1.1	1.6 to 2.2	30%	14%
Exports	Negligible	0.2	0.4	-	15%
Total	0.3	1.1 to 1.3	2.0 to 2.7	35%	14%
Annual Production (Thousands of Units)	19.7	43 to 55	75 to 94	-	-

(Note) The export ratio is based on the JIRA target value of 20% in 1990.

Source: The Long-Term Credit Bank of Japan, 1981, p. 69.

Figure 12

JIRA Estimate of Composition of IR Production in Japan (Based on Value)



Source: Research Div., The Long-Term Credit Bank of Japan, 1981, p. 73.

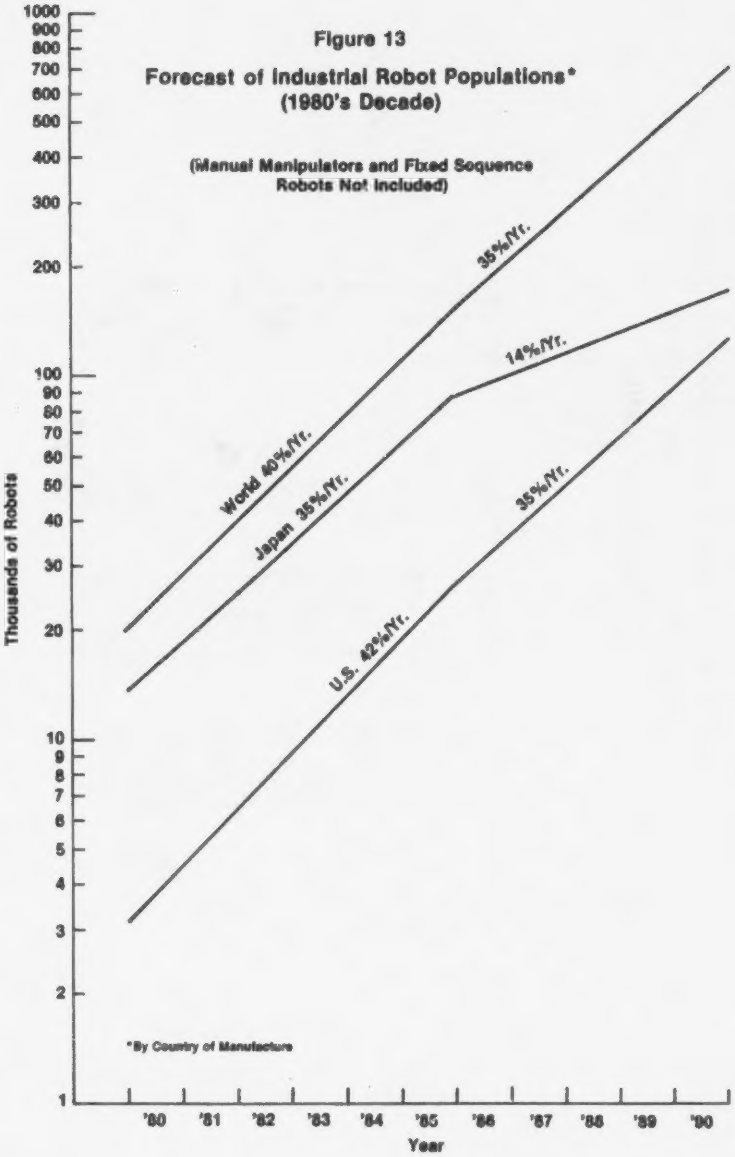


Figure 13

Forecast of Industrial Robot Populations*
(1980's Decade)

(Manual Manipulators and Fixed Sequence Robots Not Included)

*By Country of Manufacture

XVIII. Future Directions

Hasegawa (1981, pp. 169-170) makes the forecast of unfolding robot technology given in Figure 14. Based on these technological trends, he states that "...industrial robots will become smarter, smaller, quicker, lighter, stronger, more ingenious, easier to operate, more intelligent and less expensive that they are now."

Engelberger (1980, p. 118) lists in Figure 5 the qualities sought in future robots. He indicates that these qualities will be, for the most part available during the current decade. Of the missing robotic attributes, he considers the two crucial ones to be vision and tactile sensing.

JIRA (The Long-Term Credit Bank of Japan, 1981, p. 59) indicates that the technology for robot miniaturization, modularization, high speed operation, and computer control has advanced to the point where it is now available and will grow in popularity and acceptance in the first half of this decade. Technology for part recognition and position determination is also currently available, but won't receive widespread popularity until the second half of this decade. Technology for color and behavior recognition, automated assembly, and machine tool and casting robotics won't become adequately advanced until later in the first half of the decade and therefore won't achieve widespread popularity until the second half of the 1980's.

One of the greatest advantages of robotics and automation occurs in the cases where their use greatly increases equipment utilization. Albus (1981B) indicates that a robot arc welder cannot weld faster than a human, but by keeping its torch on the work about 90% of the time, versus no more than 30% of the time for a human, it can turn out 3 times as much work in the same time. If through automation more shifts can be worked, productivity is even further increased. Unfortunately, present day robots cannot set up their own work, so this reduces their productivity advantage. Albus conjectures:

Figure 14

Forecast of Robot Technology

° Materials

Lighter and stronger materials for robot structures will be developed. These will include both organic and non-organic substances. As a consequence, the size and weight of robots will decrease.

° Power Sources

Small, high-capacity power sources such as nuclear powered generators or fuel cells will allow robots greater freedom of location and movement.

° Actuators

Small, high performance actuators will appear. Robot designs will be more stylish.

° Sensors

Small, reliable, high-performance, low-cost artificial eyes, ears, and tactile sensors will be developed and even low-cost robots will have recognition capability.

° Control Systems

Advances in microcomputer technology will dramatically improve robot control. Control system costs will also be greatly reduced.

° Communications Systems

Remote control of industrial robots will be enhanced through development in fiber optics, wireless communcations, etc.

° Processing Methods

New, non-mechanical processing methods such as laser beam cutting, welding and other high-energy processing methods will reduce the processing load on robots and make the design work for them simpler.

° Robot Body Structure

Utilization of biomechanical concepts will result in superior robot structures.

° Software

Robot use will become easier through the development of robot languages, self-diagnosing systems and robot application technologies. Software will contribute to reducing the design work needed on robots.

(continued on next page)

Figure 14 (cont'd)

° Integrated Systems

Techniques for integrating production systems composed of men, machines and robots as well as their peripheral devices will be found. Further, their design processes will be computerized.

Source: Hasegawa, 1981, pp. 169-170.

> Eventually, welding robots will be sufficiently sophisticated to work from plans stored in computer memory and to correct errors which may occur during a job. Welding robots will then be able to work nights and weekends (four shifts per week) completely without human supervision. At that point productivity improvements over present methods of many hundreds of percent become possible. Unfortunately, we are a long way from that today. There are many difficult research and development problems that must be solved first. Unless the level of effort in software development is increased many fold, these improvements will not be realized for many years.

In the metal cutting industry, Albus (pp. 16-18) predicts,

> During the 1980's, robot sensory and control capabilities will improve to the point where robots can find and load unoriented parts, or in some cases, even pick parts out of a bin filled with randomly oriented parts lying on top of each other. This may improve productivity by hundreds of percent because it will make it possible to install robots in many existing plants without major re-engineering of production methods....
>
> By 1990 robots may begin to have a significant impact on mechanical assembly. There has been a great deal of research effort spent on robot assembly. Unfortunately, the results have not been spectacular--yet. On the one hand, robots cannot compete with classical so-called "hard automation" in assembly of mass produced parts. General purpose machines like robots are still too slow and too expensive to be economical for mass production assembly tasks. On the other hand, robots cannot yet compete with human assembly workers in small lot assembly. Humans are incredibly adaptable, dexterous, as well as fast, skilled, and relatively cheap compared to robots...
>
> Nevertheless, progress is being made and will continue. Robot capabilities will gradually increase. Sensory systems will become more sophisticated and less expensive. The cost of computer hardware is dropping rapidly and steadily with no sign of bottoming out. Software costs are likely to be the major impediment to robot development of the foreseeable future, but even these are slowly yielding to the techniques of structured programming and high level languages.
>
> Eventually, extremely fast, accurate, dexterous robots will be programmed using design graphics data bases which describe the shape of the parts to be made and the configuration of the assemblies to be constructed. Eventually, robots will be able to respond to a wide variety of sensory cues, to learn by experience

> and to acquire skills by self optimization. Such skills can then be transferred to other robots so that learning can be propagated rapidly throughout the robot labor force.
>
> Sometimes, perhaps around the turn of the century, robot technology will develop to the degree necessary to produce the totally automated factory. In such factories robots will perform most, if not all, of the operations that now require human skills. There will be totally automatic inventory and tool management, automatic machining, assembly, finishing, and inspection systems. Automatic factories will even be able to reproduce themselves. That is, automatic factories will make the components for other automatic factories.
>
> Once this occurs, productivity improvements will propagate from generation to generation. Each generation of machines will produce machines less expensive and more sophisticated than themselves. This will bring about an exponential decline in the cost of robots and automatic factories which may equal the cost/performance record of the computer industry...
>
> Eventually, products produced in automatic factories may cost only slightly more than the raw materials and energy from which they are made.

In summary, what we see emerging are robots with increasing intelligence, sensory capability, and dexterity. Initially, we will see an increasing use of off-line programming of computer-controlled robots, using improved robot command languages. Provision will be made to include the role of sensors, such as vision and touch, in this programming. Later, self-planning will emerge as higher and more general commands are given to the robot. At this point, the marriage of robotics and artificial intelligence will be virtually complete. At the same time as all this is taking place, robotic hands with improved dexterity (so that it will not be necessary to move the entire arm for fine motions), and advanced control systems to support this dexterity, will emerge. Also emerging will be robots with coordinated multiple arms and eventually even legs, supported by even more sophisticated control systems.

As this evolution progresses, information and intelligence will become the dominant factor in robotics, with the manipulator devices and sensors shrinking in importance to the skeleton that undergirds this dominating "ghost in the machine".

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report provides an overview of the rapidly changing field of robotics. It is intended to be read by the technically oriented layman, such as engineering managers, government funding offices, and others who desire an overall perspective of the field but are unable to obtain it from the highly technical and unintegrated literature in the field, or from the more flamboyant but non-technical feature articles in the popular press.

The report incorporates definitions of the various types of robots, a summary of the basic concepts utilized in each of the many technical areas, review of the state-of-the-art and statistics of robot manufacture and usage. Particular attention is paid to the status of robot development, the organizations involved, their activities, and their funding. A 5-10 year forecast of the emerging technology is also included.

The majority of the material in this report is drawn from the activities in the U.S. and Japan, the principal players in the world of robotics.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Applications; Forecast; Japan; Overview: Research and Development; Robot; State-of-the-art.

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Mr. GORE. Thank you very much, and thank you for the work you are doing, too.

Now, representing the National Bureau of Standards, Dr. John Lyons. Dr. Lyons, welcome.

STATEMENT OF DR. JOHN W. LYONS, DIRECTOR, NATIONAL ENGINEERING LABORATORY, NATIONAL BUREAU OF STANDARDS, ACCOMPANIED BY JAMES S. ALBUS, ACTING CHIEF, INDUSTRIAL SYSTEMS DIVISION

Dr. LYONS. Thank you, Mr. Chairman.

It is a pleasure to appear before the subcommittee and to discuss your questions in the context of the NBS program on automation. We assume when you use the word "robotics" the we may expand that to include flexible manufacturing systems.

Mr. GORE. Yes, absolutely.

Dr. LYONS. I noticed you did that in your opening remarks.

Mr. GORE. That is just the next step, it seems like. Are these charts to accompany your——

Dr. LYONS. Yes, I am going to refer to those.

Mr. GORE. Could you turn it a little bit so our guests in the audience can also follow them?

Dr. LYONS. We have provided you with a set of small versions of those if you have any trouble seeing those at a distance.

Mr. GORE. Good.

Dr. LYONS. I have with me Jim Albus, who is a well-known author of books on the subject of robotics and is serving as the division chief in our Center for Manufacturing Engineering, which is the term we use for production research.

In our program we are addressing the discrete parts manufacturing industry, which accounts for 75 percent of commerce in this country in manufactured goods, and when I say discrete parts I mean the kind of parts that one makes to sell to the auto industry. Thirty-five percent of U.S. firms are engaged in such manufacture, and most of those firms are very small, employing on the order of 50 people or less, some 100,000 companies of that size. So we are talking about small machine shops, typically.

The Bureau's program addressing this industry is attempting to deal with the concept of a fully automated flexible manufacturing system. Such a system would be made up of metal-cutting machines, computers and terminals, robots, conveyors, and inspection stations. We have restricted our program to cutting of parts and we have omitted from the program, at this stage anyway, the assembly of the parts. Therefore, we are talking about making a machined part.

The National Bureau of Standards' role with this industry is an outgrowth the traditional approach that we have always taken and for which we were created. Namely, we are to provide measurement assurance to industry; we are to assist with the necessary voluntary standards that they require; and we perform supporting basic long-term research. I will address all three of those components in my remarks.

First, let me show you how we got into this business. About 80 years ago when the Bureau was formed, the machine shop had to know the dimensions of the part that it made—this by the well-known micrometer. The Bureau's role is to provide a calibrated artifact called a gage block—and here is one. On the chart you see a whole boxfull of these gage blocks. Our service to the industry is to calibrate the set and provide them. The machine shop puts the block in here, adjusts the micrometer to the proper zero for the proper dimension—in this case it is a 2-inch block—and that is the measurement assurance. He now knows if he makes something and this tells him it is 2 inches, he can sell that to somebody else and if there is any dispute it will come back to the National Bureau of Standards. That is our primary role.

This is a chart showing many such artifacts, from screw threads to roundness of balls and even screens, the sizes of holes in screens. We have done this, as I say, for very many years and that is our traditional role, and we still do it because there are still lots of machine shops that go no further than the simple gauge block.

However, as machined parts became more complex, we had to move into three dimensions. The industry moved into three dimensions using what is called a three-dimensional coordinate measuring machine, on the next visual. If you look closely at that—and you may need your little version to see it will—it looks very much like a machine tool. It has finely machined ways that go in the X and Y directions as well as in the vertical direction. The only difference is, it does not cut, it measures.

What is the Bureau's role with respect to the 3-D coordinate measuring machine? Well, it is twofold. First, you want to know that when the head goes to a certain place to make a measurement, it knows very accurately where it is. We provide the equivalent of a gauge block; namely a three-dimensional ballplate—see the previous chart. That device with the cones with the balls on top is a technique for establishing precisely where in space the measuring machine is.

The second thing that we had to do with these coordinate measuring machines was to map the errors because, even though it is a very finely machined device, it still moves in space more than one anticipates and there are errors in some 21 different degrees of freedom on the machine. We had to find all of those errors, map them, and then build them into the computer which runs it. This is a computer-operated measuring machine. It is now a self-correcting three-dimensional coordinate measuring machine. Therefore, we provide two services, the ball plate and the methodology for correcting the errors in the machine.

Well, it did not take us very long—and by the way, we started doing that work about 10 years ago and have now completed it—it is not much of an intellectual jump to say if you can do a self-correcting measuring machine, you ought to be able to do a self-correcting cutting machine. Therefore, we have taken the same approach—that is, error mapping—and moved it onto the machine tools themselves.

Now the concept involved in this I think is very significant. It is a little bit high-risk, and that is probably one reason why the Government ought to do it. We call the idea "deterministic metrology." The whole point is, one focuses on the process or on the machine tool and not on the part. We say that if you can account for all the errors, both static and thermal, in a machine tool, then there is every reason to think that it will make the correct part every time. You would have 100 percent right-first-time, as compared to current practice which is about 30 percent rejects.

Furthermore, one can save time in the process and if one can put into the process such corrections, one does not have to measure the part afterward on a 3-D coordinate measuring machine except occasionally. One can actually save about 50 percent of the production time. That is to say, it takes as long to measure the product with one of these machines as it does to cut it in the first place. What we are trying to do is move the metrology and the measurement assurance onto the machine.

On the next visual we show a sketch of a work station which is a robot feeding a horizontal machine tool with associated conveyors. We are building such a work station this year and expect to demonstrate this "deterministic metrology" approach which is really the ultimate in the Deming approach. You will remember that Dr. Deming approached the process and not the product, and that is what we are doing in this work.

This work station will actually be part of a fully automatic research facility, what we call the AMRF, which is being installed in the Bureau's instrument shop at this time. It will take us 2 or 3 years to get it built. We will have a set of such cells which will constitute actually a flexible manufacturing system at NBS.

Mr. GORE. Dr. Lyons, let me interrupt you at that point. We have a vote on the floor, and it will not take very long to get over there and back, about 6 or 7 minutes. Therefore, with your indulgence and that of the other witnesses we will take a very, very brief recess and then pick it up.

[Recess taken.]

Mr. GORE. The subcommittee will come back into session.

I am sorry for the delay and disruption. I believe we were discussing "deterministic metrology," Dr. Lyons, if you want to proceed.

Dr. LYONS. The question is whether I can still throw strikes.

Actually, I had finished with that topic, Mr. Chairman. I wanted to shift to the second part of the three parts that I had mentioned earlier, and that is interfaces between components and the need for voluntary consensus standards. Let me define "interface" first.

In this exhibit I show a series of components in a computer-integrated manufacturing system, where you have the computer-aided design or CAD system at the top, maybe even at a different geographic location in a design shop, interacting with another CAD system which may be more closely related to the manufacturing process. That, in turn, relates to the computer-aided planning system on the left and the computer-aided production planning on the right, which are two aspects of running the plant. Then we have a materials-handling computer-aided system there, and finally the heart of the flexible manufacturing system, which is the computer-aided manufacturing components.

Every place we have a question mark we have an interface, and within the CAM system itself there would be several such interfaces, if you visualize the series of cutting tools, robots, and the like.

Mr. GORE. What is the MIS?

Dr. LYONS. The management information system, which is the feedback loop which tells you the status of all of those machines.

Mr. GORE. All right.

Dr. LYONS. Therefore, all of those are computer aided devices. They are typically individually manufactured. If you buy from different manufacturers, it turns out they cannot talk to each other because the computer software is proprietary. In fact, that is the principal advantage that the manufacturers have—the software. Therefore, if you are a large firm you buy all these different components and you create your own interfaces which may be hardware, plugs, but more importantly there has to be a software interface. It has to be in common format so that data can come from one system through this nonproprietary interface and then back into the other system.

If you are a small manufacturer, you do not have the expertise to develop those, interfaces so you are stuck. As I indicated, almost 90 percent of the people in this business have less than 50 employees, so somebody has to get people together and develop the software and hardware interfaces between devices.

An example of this is the initial graphics exchange specification, which was developed to allow one computer-aided design system to talk to another. The need for that interface among the people that make such systems and the users and the Government—particularly in the form of the Air Force—was felt so strongly that this activity came together with essentially no top-down planning at all. The participants got together, the Bureau coordinated and served as a third party in the activity, did a little bit of the technical work, and convened the groups.

The people who participated in that—again, you cannot see, the detail on the chart I am sure, but you have a handout—the point of this list is to show the large number of distinguished firms who make and use computer-aided design systems.

Another indication of the need is that this was published as a national standard within 18 months of submission, which we believe is probably a record for a consensus standard.

Now to emphasize the need for this kind of R&D and standards development in the software part of this program, I want to read from my testimony just two quotes. The first is a quote from a report of the National Academy of Sciences, from Yoshikawa and others and it says:

> Unless great strides are made towards modularity and interface standardization in the near future, the level of expertise required to design and assemble large CAD/CAM systems could severely limit their proliferation.

Second, a quote from Electronics magazine last fall—and this is an interesting one, it relates to our Japanese friends:

> Experts agree that a key stimulus to FMS sales will be adoption of standardized software which would cut costs and reduce confusion. The Japanese worry that the U.S. is progressing far more rapidly toward this end, jeopardizing Japan's present lead in FMS. "Japan as a country is not moving toward standardization of software and information," laments Wakasuge of Hitachi Seiki. "The U.S. is frightening."

I find that an interesting quote. The Bureau's efforts are intended to facilitate and hasten the adoption of our software standards.

Then, finally, the last component of our program is our basic research in support of these efforts, and I will just mention them. They are described more fully in the testimony. They relay to wave optics on ultrasmall dimensions, submicron measurements, inverse scattering research and image reconstruction from scattering, the study of hierarchical control systems, research that Dr. Albus is much involved in, that branch of artificial intelligence that applies particularly to these manufacturing systems, robots, and of course fundamental research on measurements and sensors.

We do this research in part to make sure that the more applied programs are at the state of the art but, more importantly, so that our standards efforts are sufficiently well-informed that we avoid the danger of freezing technology by issuing an improperly drafted standard, which we think is an important point.

Thank you, Mr. Chairman.

[The prepared statement, plus charts mentioned in Dr. Lyons, oral presentation follow:]

STATEMENT OF
DR. JOHN W. LYONS
DIRECTOR
NATIONAL ENGINEERING LABORATORY
NATIONAL BUREAU OF STANDARDS

BEFORE THE

SUBCOMMITTEE ON INVESTIGATION AND OVERSIGHT
COMMITTEE ON SCIENCE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

JUNE 23, 1982

Mr. Chairman and Members of the Subcommittee: it is a pleasure to appear before this Subcommittee to discuss robotics technology and to assist the Subcommittee as it assesses the importance of this technology to the Nation and considers the role the United States Government should play.

In this statement I address this Subcommittee's questions in terms of the relevant work at the National Bureau of Standards; namely, the automation program in our Center for Manufacturing Engineering. I assume that the Subcommittee includes in robotics technology the systems in which robots are embedded such as flexible manufacturing systems (FMS). I have with me Dr. James S. Albus, an expert on the technical aspects of such work and a well-known specialist on robotics. Dr. Albus is a key member of the professional staff of the Center for Manufacturing Engineering. He is here to assist us in answering your questions.

At NBS we are addressing the measurement and standards requirements of the automation of the discrete parts manufacturing industries such as those supplying parts for aircraft, automobiles, and the like. These industries produce goods that account for 75% of all U.S. trade in manufactured goods. Although this sector of the U.S. economy includes 35 percent of all U.S.

firms, over 100,000 of these firms (or 87 percent of the total) have less than 50 employees. It now appears that these industries must automate to successfully compete, in both foreign and domestic markets, with Japan, Germany, and other industrial countries which have major government sponsored programs in automation.

I now turn to that aspect of automated manufacturing we have chosen to work on; namely, the completely automated small-batch manufacturing system, or flexible manufacturing system. It consists of such elements as metal cutting machines, computers, terminals, robots, conveyers, and measuring or inspection systems. Such a system produces a variety of shapes and sizes of parts and may proceed to assemble them into larger systems; for example, gears, shafts, and cases into transmissions. At NBS, we are restricting ourselves to the metal cutting processes to make the individual parts.

The role of NBS in automated manufacturing is to provide the basis for measurement assurance (metrology) including traceability to National standards and to assist in the development of those voluntary standards necessary for industry to successfully automate. We also carry out related basic and exploratory research as needed. I shall now describe the NBS program in terms of the two principal thrusts giving the background for each and outlining our present efforts.

Historically, the American machine shop has relied on NBS for assurance that the measuring devices used in the machine shops provide the right answer. The shop micrometer was (and is still) adjusted by inserting a block of metal whose dimension is certified by the Bureau. NBS still calibrates sets of carefully characterized gage blocks for such use. This service enables the user to trace his measurements back to the primary unit of length in the United States. This service is one of the core functions of the Bureau. Gage blocks were, and are, fine for simple measurements. As machined parts became more complex, however, so did the measurement technique. In the past twenty years measuring machines operating in three dimensions have been introduced to the manufacturing shop. These machines automatically measure many points on the suface of a complex shape, often under computer control. The part is passed or failed by comparing the coordinates of the measured points with production specifications. NBS provides two services: three-dimensional test structures, and a methodology for preparing error maps of the measuring machine. The test structure is the three-dimensional equivalent of the one-dimensional gage block mentioned earlier. The methodology to make error maps enables the maker of the measuring machine or its user to incorporate self-correcting software in the computer operating the test machine. This technology is beginning to be used in shops across the country.

We see a next stage beyond the three-dimensional coordinate measuring machines, however, and we are focusing our metrological efforts on it. The three-dimensional coordinate measuring machines require nearly as much time to make the measurement as that needed for the original machining work. Production time is therefore lengthened by this amount. Further, the part is measured after it is made and therefore the measurement serves to make a decision to accept or reject but does not directly affect the manufacturing process for that part. We believe that measurement assurance will be directed to the process, not the part, and that it will be possible to control this process such that it only makes acceptable parts. We call this approach "deterministic metrology." Let me amplify why we believe this to be so.

Our success with the self-correcting three-dimensional coordinate measuring machines suggested that one should be able to achieve a self-correcting machine tool. There are additional problems to be addressed such as errors from thermal distortion from the heating from the motor drive, bearing friction, and cutting head. But, in principle, one should be able to account for all the contributions to machine error, correct them in the software of the machine controller, and have a machine which cannot make a bad part. An exception would be a mechanical failure in the system. Otherwise, the machine must make acceptable parts. Hence the term "deterministic."

In view of this likely development NBS must be ready to provide means and methods of traceability to National standards consistent with this new way of looking at quality control. We have taken this idea far enough to be confident of ultimate success. There are many details to be addressed but the major items are falling into line. We are applying the concepts to a fully computerized vertical milling machine at NBS this year. We plan to test them further in the Automated Manufacturing Research Facility (AMRF) now being installed in the NBS machine shop. This is to be a small flexible manufacturing system to serve as a test bed to see if our measurement concepts will provide the assurance required by American industry.

The deterministic approach I have just described has two very desirable features: it shortens the production time and it raises the right-first-time percentage. Post-production inspection will be no longer the key hurdle it has been in the past, serving as a double check instead. For the most stringent specifications we foresee additional sensors installed on-line to provide dynamic, real-time direct measurements of the parts in process. We already see such techniques in the most sophisticated equipment such as diamond turning machines fitted with laser sensors.

The AMRF is also designed to be the test bed for the standards needed for automated systems. We are primarily concerned with standards for the many interfaces between components of computer-aided manufacturing (CAM) systems, and interfaces between the system and the design, planning, and control of the manufacturing operation. In a typical system there will be computer-aided design (CAD), computer-aided planning (CAP), computer-aided production planning (CAPP), and computer-aided manufacturing. These will in many cases be integrated by a master computer (computer integrated manufacturing, (CIM)). There are many interfaces in such a system. The CAD system must be able to interact with the CAP and CAPP systems and with the various parts of the CAM system. Within the CAM system the robot must interact with the computer controlling the robot/machine combination as well as with the machine it is serving. Wherever there is a pair of computer-aided components interacting there is an interface. If the components are made by different manufacturers it is a fact that they cannot now be coupled directly except by custom-made software interfaces. Building such interfaces one at a time is costly and requires very skilled staff. Furthermore such efforts are beyond the reach of the small-to-medium machine shop. Therefore, the large shop may be discouraged by the cost and the small shop either buys whatever he can get from one supplier, or doesn't enter the field. This situation creates a substantial barrier in the market for automated systems. Currently, no single firm can eliminate this barrier.

What is needed is a series of non-proprietary interfaces such that two components can interact through it without having to reveal proprietary software. Such non-proprietary interfaces may be developed as consensus standards wherein all the concerned parties agree to have one and only one format for the interface between CAD systems, only one between robots and milling centers, only one between CAD and CAP systems, and so on. NBS' usual role in such standards development is to work on the technical details, validate in the laboratory, and make proposals to the concensus standards bodies. We have recently completed successfully the first phase of a standard for the CAD-CAD interface. The standard, known as Initial Graphics Exchange Specifications (IGES), has been issued by the American National Standards Institute just 18 months after the ideas were introduced - a near-record for such a development. NBS coordinated the development of this standard on behalf of a large number of manufacturers of CAD systems and a large number of users. This effort was sponsored by the Department of Defense. We were able to perform this service because of our position as a neutral third party and because of our technical knowledge in the field.

To underscore the importance of these interface standards I offer two quotes. The first is from Yoshikawa, Rathmill, and Hatvany in their study for the Committee on Computer-Aided Manufacturing of the National Academy of Sciences:

> "Unless great strides are made towards modularity and interface standardization in the near future, the level of expertise required to design and assemble large CAD/CAM systems could severly limit their proliferation."

The second quote is from Electronics magazine (October 6, 1981 p. 88):

> "Experts agree that a key stimulus to FMS sales will be adoption of

> standardized software, which would cut costs and reduce confusion. The Japanese worry that the U.S. is progressing far more rapidly toward this end, jeopardizing Japan's present lead in FMS. 'Japan as a country is not moving toward standardization of software and information,' laments Wakasugi of Hitachi Seiki. 'The U.S. is frightening.'"

NBS efforts are intended to facilitate and hasten this adoption.

Finally, we are conducting high risk basic and exploratory research in support of the measurement and standards efforts. We conduct basic research in wave optics to understand how to reconstruct images from scattered radiation including better analytical techniques for the deconvolution of data obtained in inverse scattering experiments, to develop improved measures of ultra-small dimensions and to improve precision and accuracy at the submicron level. We are probing for better organization of the smart elements in a hierarchical system (artificial intelligence research). Some of the exploratory work is on sensors such as those needed in the next generation of smart robots. Vision systems require better sensors, better computer algorithms, and new ways of using the results. NBS is conducting research of this type, substantially beyond current industrial efforts, to provide seeds for the future. We are careful to avoid going so far that we run any risk of harming future patent estates of the private sector but hope we go far enough to stimulate future private sector efforts. The conduct of such research is essential for NBS to assure that the current program is at the state-of-the-art and that we can anticipate the future and avoid any actions that might inhibit subsequent developments in the technology.

Mr. Chairman, I have discussed the automation and robotics technologies in terms of the NBS role and response. I have described our program in some detail to show how the NBS mission of measurement and standards support to industry is being applied to help facilitate industry's adoption of this new manufacturing technology. I hope we have been responsive to the Subcommittee's needs. Dr. Albus and I shall be pleased to take questions.

JOHN W. LYONS

Date of Birth: November 5, 1930

Birthplace: Reading, Massachusetts

Education: Degrees

Harvard University, A.B., Chemistry
1952
Washington University, A.M., Physical Chemistry
1963
Washington University, Ph.D., Physical Chemistry
1964

Position:

Director
National Engineering Laboratory
National Bureau of Standards

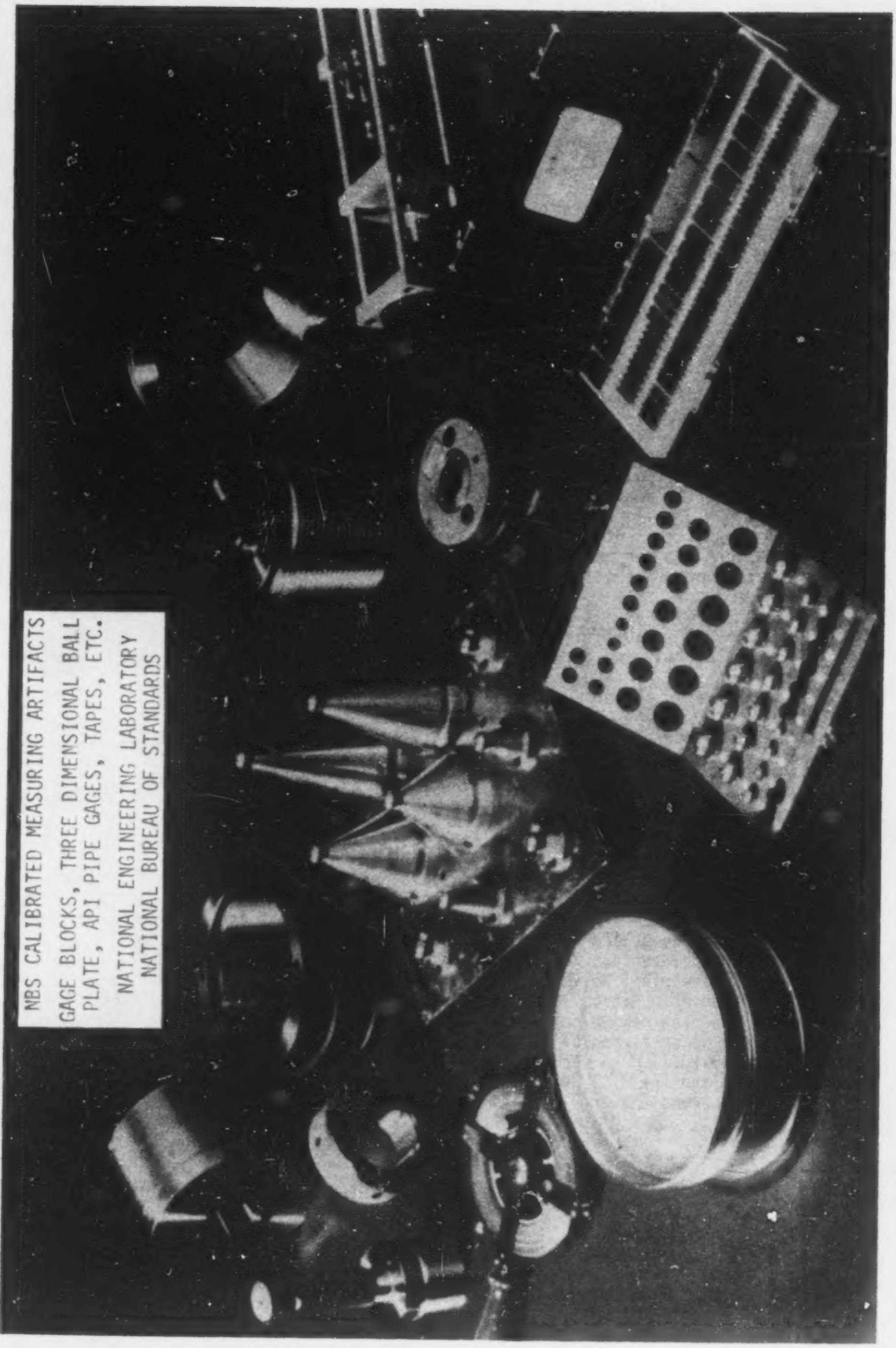
As Director of the National Engineering Laboratory, Dr. Lyons is responsible for NBS's research in applied mathematics, building technology, electronics and electrical engineering, energy conservation, engineering standards development, fire, manufacturing engineering, and chemical engineering.

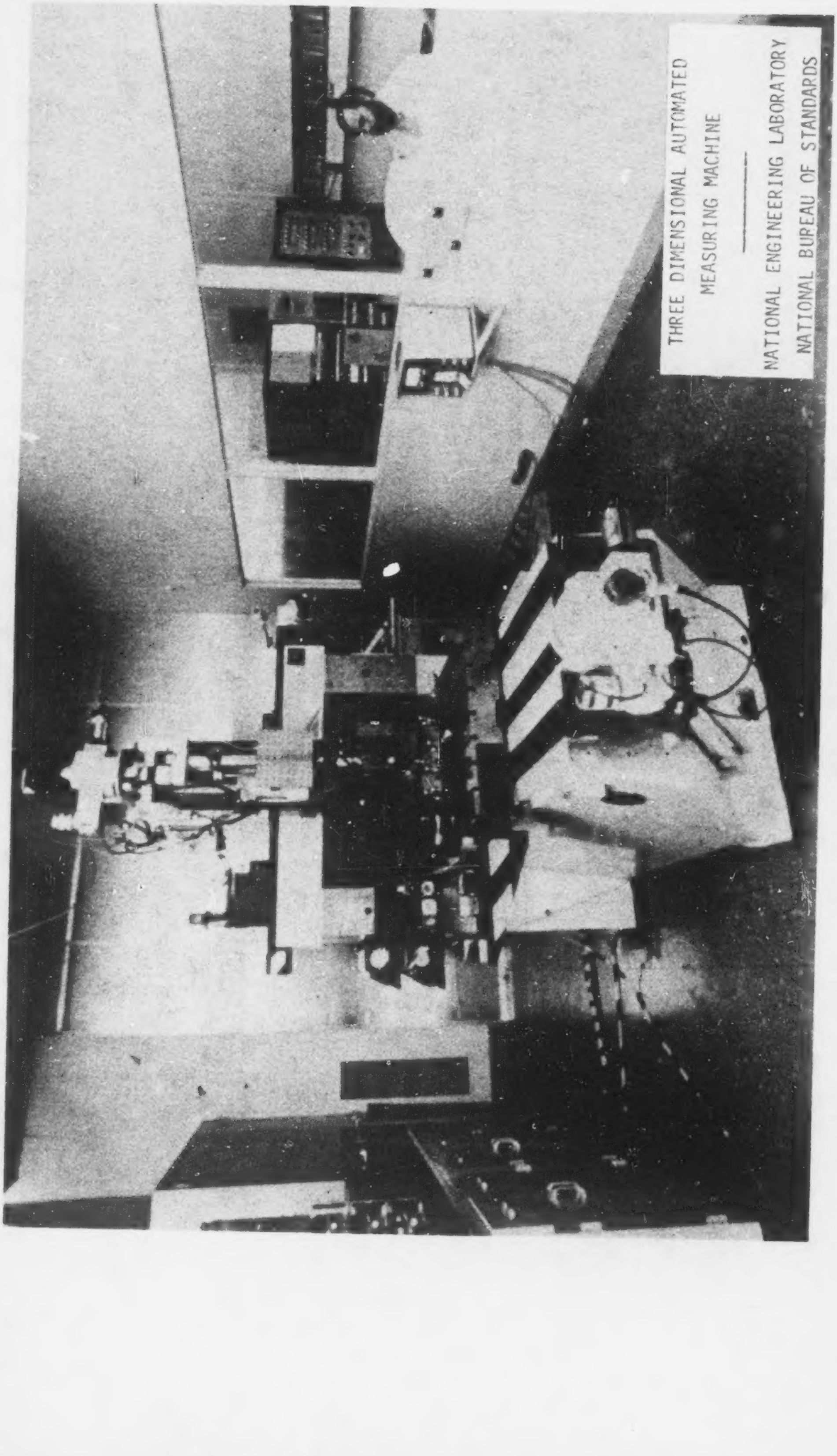
Dr. Lyons was Director of the NBS Center for Fire Research until December 18, 1977, and was responsible for providing scientific and technical knowledge applicable to the prevention and control of fires.

Dr. Lyons served in various research and development positions at the Monsanto Company from 1955 to 1973. He specialized in the chemistry and uses of phosphorus-based chemicals including fire retardants. He served from 1971 to 1973 as a member of the ad hoc panel of fire research, a National Academy of Sciences evaluation panel for the National Bureau of Standards.

Dr. Lyons is author of two books: Viscosity and Flow Measurement and The Chemistry and Uses of Fire Retardants. He has contributed chapters to five other books and has written numerous papers and articles on technical or research topics. His early research interest was the physical chemistry of polyelectrolyte solutions, especially formation of complexes with metal ions. This work emphasized the behavior of inorganic polyphosphates and desoxy ribonucleic acid (DNA).

Dr. Lyons is a Fellow of the American Association for the Advancement of Science, Fellow of the Washington Academy of Science, member of the American Chemical Society (past chairman of the St. Louis Section), member of the American Institute of Chemical Engineers, and member of Sigma Xi. He serves on the Advisory Committee for Engineering, National Science Foundation; Advisory Council, College of Engineering, University of Maryland; Board of Directors, National Fire Protection Association. He was chairman of the Products Research Committee (1974-1979), a nine-member charitable trust administering a $5M research fund on fire research; co-chairman of the US-Japan National Resources Panel of Fire Research (1975-1978). He received the Presidential Management Improvement Award in 1977 and the U.S. Department of Commerce Gold Medal, also in 1977. In 1981 he received the Presidential Rank Award of Distinguished Executive.

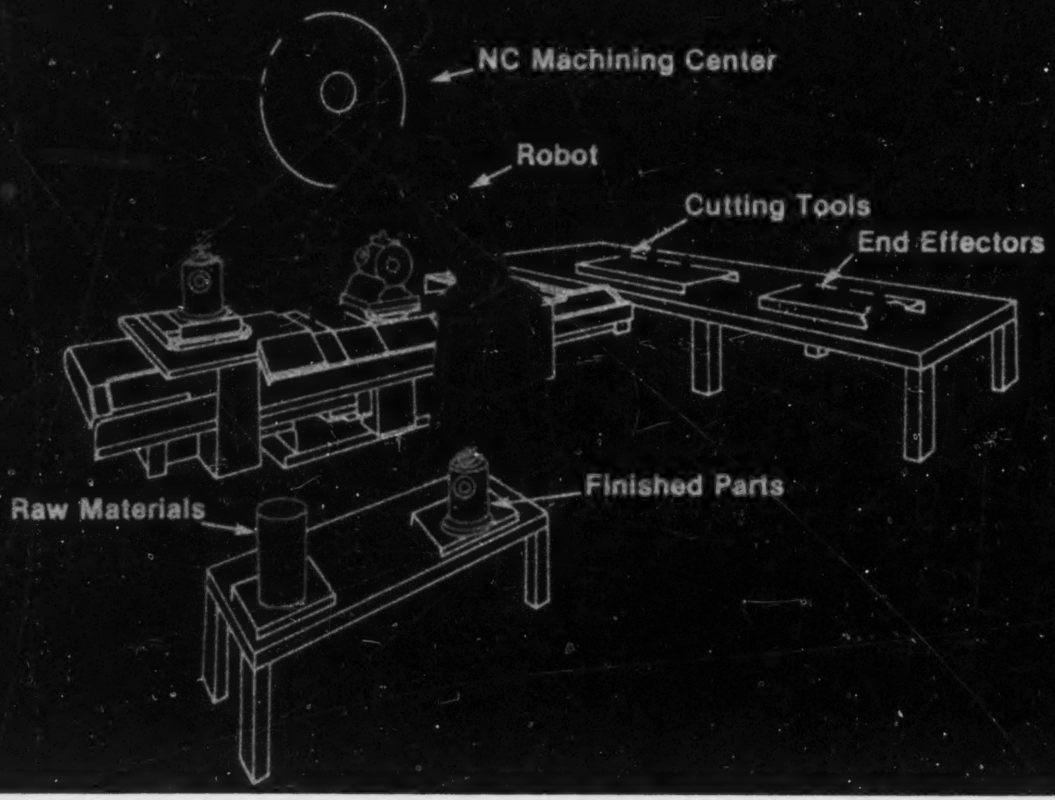

NBS CALIBRATED MEASURING ARTIFACTS
GAGE BLOCKS, THREE DIMENSIONAL BALL
PLATE, API PIPE GAGES, TAPES, ETC.
NATIONAL ENGINEERING LABORATORY
NATIONAL BUREAU OF STANDARDS



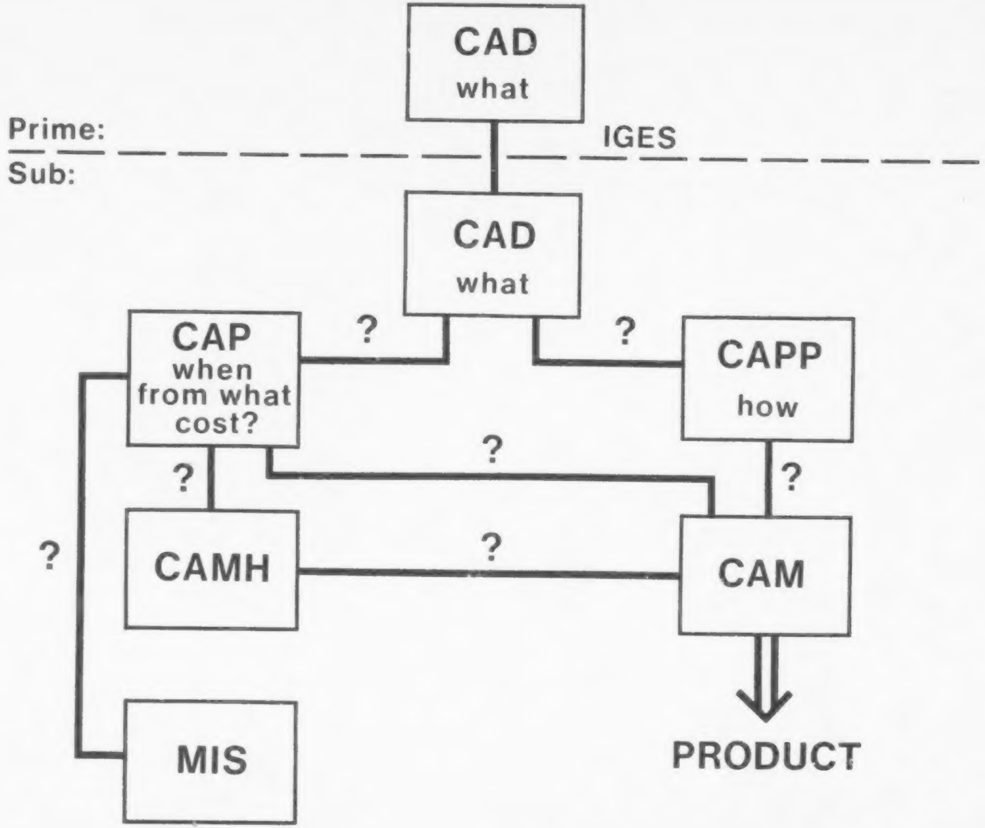
THREE DIMENSIONAL AUTOMATED
MEASURING MACHINE

NATIONAL ENGINEERING LABORATORY
NATIONAL BUREAU OF STANDARDS

Horizontal Machining Workstation


NC Machining Center
Robot
Cutting Tools
End Effectors
Raw Materials
Finished Parts

COMPUTER INTEGRATED MANUFACTURING


CAD
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MIS
PRODUCT

IGES VENDORS AND USERS

Industry representatives from over forty companies now serve on one or more of the committees currently working to extend and monitor the implementation of IGES.

Advanced Technology, Inc.
Applicon
Auto-trol
Aydin Controls
Bechtel
Bendix
Boeing
CALMA
CAM-I
Combustion Engineering, Inc.
Computervision
Control Data
DMT Corporation
DuPont
Evans and Sutherland
Ford
General Dynamics
General Electric
General Motors
Gerber
Graftek
Harry Diamond Labs
Holquin and Associates
Hughes
IBM
International Harvester
John Deere
Lockheed Missiles & Space
Manufacturing Data Systems, Inc.
Martin Marietta
McDonnell Douglas Automation Co.
NASA
National Bureau of Standards
National Computer Systems
Newport News Shipbuilding
Ocean Data Systems
Racal Redac
Rockwell International
Sandia Labs
Society of Manufacturing Engineers
Structural Dynamics Research Corp.
Time Engineering
Union Carbide
U.S. Air Force
U.S. Army
U.S. Navy
Vought
Westinghouse
Xerox

Mr. GORE. Now the IGES is the integrated graphics exchange system?

Dr. LYONS. It is a specification.

Mr. GORE. A specification.

Dr. LYONS. It is really a format so that data can emerge from one CAD system in the proper format, go through this nonproprietary interface, and then be received by another CAD system which knows that the same data format is used. What it really is is an agreement among all parties to format information—and it is only selected information. You know in advance how it is going to come, in what form it is going to come, and the rules of the game, the grammar, if you will, of the software.

Mr. GORE. To allow the parallel developments of a system to be later assembled from one—that is made up of a combination of different suppliers, manufacturers, and so forth.

Mr. LYONS. That is right. Ultimately, such standards would allow you to pick and choose those things that are best suited to your use without having to worry that there would not be any way for it to talk to the other machines that you purchased.

Mr. GORE. These are all American companies?

Mr. LYONS. As far as I know.

Mr. GORE. Well, I will hold questions until after the panel has completed its testimony. Dr. Edith Martin, we are honored to have you with us here today, the Deputy Under Secretary of Defense for Research and Advanced Technology. Please proceed.

STATEMENT OF DR. EDITH W. MARTIN, DEPUTY UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ADVANCED TECHNOLOGY, DEPARTMENT OF DEFENSE, ACCOMPANIED BY LLOYD LEHN, ASSISTANT FOR MANUFACTURING TECHNOLOGY

Dr. MARTIN. Mr. Chairman and the committee, I am pleased to be here today.

DOD breaks its robotics activities, as you have it described in your earlier testimony, into two components. My office is responsible for the DOD's science and technology efforts, that is, the 6.1, 6.2, and 6.3A programs, and thus we have responsibility for the technology efforts related to robotics.

The Deputy Under Secretary of Defense for Acquisition Management, on the other hand, has the responsibility for the industrial base.

DOD, as you may know, has been active in support of U.S. capabilities in robotics and artificial intelligence for over 20 years. Examples of this in the Office of Naval Research and DARPA, and robotics centers which have been established at Carnegie-Mellon and MIT.

I will mainly address my responses to questions that were provided by the committee. These responses are DOD's perspective and reflect DOD mission needs.

Your first question inquires about the appropriate role of the U.S. Government in robotics research. The Federal Government we believe should be supportive and nurturing. However, we feel it should not be directive nor regulatory. The Federal Government can provide robotics support in five areas.

First, basic research: This has been mentioned by some of my colleagues here. We must understand that robotics is not an isolated technology. It is an integration of computer hardware and software, sensors, actuators, and so forth. Over the years, DOD has provided continued support to these topic areas individually and will continue to support a broad base of robotics-related technologies.

Second, the Government can provide support to higher education. It can subsidize centers of excellence and provide seed money or other incentives to create the curricula needed to support the robotics work force. The Air Force is currently planning to select and support two universities at about $1 million a year over a period of the next 4 years. This is in addition to three already supported by the Office of Naval Research.

The Government can facilitate robotics activities by the sharing of information. DOD has 20 information analysis centers, or IAC's as we call them, and these disseminate information on specific technologies. Some examples are metal matrix composites, infrared technology, and plastics. The Government could establish such a center for robotics information.

Another possible contribution is in the area of standardization. While it may be premature, the Federal Government can provide a forum in which industrywide standards can be discussed. There will be a need in the future for standards in areas such as safety, nomenclature, and terminology—that probably should not wait—mechanical and electrical interfaces, as has just been stated, software, and man-machine interfaces. With regard to standardization, of course we assume that these would be primarily under the aegis of the National Bureau of Standards but that mission areas such as DOD would take a very active role, especially in specific requirement areas.

The Government could support mission-essential technology. Now for DOD, the most important contributions would be in three principal mission areas. Our objectives, our primary objectives are first to attain whatever tactical advantage robotics might provide; next, to avoid technical surprise by an adversary; and last, to promote effective, efficient, and economical production of defense materials.

Now as far as your second question concerning the nature of robotics research which is currently being conducted or funded in the Federal Government, as mentioned earlier robotics technology encompasses many disciplines. It encompasses computer science, artificial intelligence, optics, acoustics, and mechanical and industrial engineering. DOD has numerous applications in multiple mission areas and these are stated in my written statement.

Funding of robotics technology programs supported by DOD totals $26.7 million in fiscal year 1982. It will be $44 million in fiscal year 1983. A detailed breakdown can be found on page 11 of the prepared text.

This funding supports primarily two areas: Science and technology programs in robotics and the industrial base programs in robotics. The purpose of the science and technology programs is to develop and extend fundamental knowledge and theory to support systems development and applications. Some areas under study include spatial reasoning, image understanding, and language understanding. Representative prototype hardware and software under development are advanced hand/eye/arm manipulators and 3-D vision sensors and image processing.

Industrial base programs in robotics focus on engineering problems such as machine control languages, mobility, and portability of robots, and materials handling.

I would like to proceed to your third question concerning long-range research needs to be fostered by the Federal Government to insure competitiveness in robotics technology.

Our interest in application of robotics is to the combat environment and in enhanced manufacturing and the maintenance of weapons systems. DOD long-range research needs are clustered into three scientific disciplines.

Research topics include the development of languages for controlling robots, special algorithms for the control of robotic joints, and system integration of robots into systems of machines.

Second is mechanical and industrial engineering. Topics here address the means for increasing the speed of robots, improving their accuracy, and enhancing their dexterity.

The third discipline is electronics. The electronics research topics focus on improving computational hardware and electronic sensors to enable the robots to interpret their environment.

Your fourth question addresses efforts being made to coordinate Federal robotics research. The level of effort in DOD, specifically in the robotics technology area, is relatively low and, as I think we have heard from others, coordination is mainly informal and on an ad hoc individual basis. Review of robotics efforts, however, is an integral part of the normal DOD budget formulation and review process.

Now that is robotics. The DOD coordination of industrial manufacturing is conducted in the Office of Acquisition management via, in part, the manufacturing technology program. We also have coordination of industrial manufacturing conducted by the CAD/CAM Subcommittee of the Manufacturing Technology Advisory Group.

Your last question asked about a national plan to promote robotics technology. We question the feasibility of a national plan. Such a plan connotes a growth in bureaucracy and perhaps unnecessary regulatory constraints. We believe the Government should rely in large on the incentives of the free enterprise system to encourage the use of robots in the industrial base. In addition, it is possible to provide tax incentives or other economic motivators to expedite the process.

We propose as an alternative, voluntary information sharing via robotics forums and participation in national interest activities such as standardization. DOD would be quite willing to participate in periodic conferences, workshops, et cetera, to facilitate information exchange.

In conclusion, I would like to state that it is apparent that the advancement of the state of the art and the application of robotics and related technology is important to the future of the Nation and to DOD's ability to provide for the national defense needs.

We appreciate the interest and concerns that have been expressed by scheduling this hearing on what we feel is an important topic, and I am pleased to have had the opportunity to provide DOD input to your deliberations.

[The prepared statement of Dr. Martin follows:]

PREPARED STATEMENT OF DR. EDITH MARTIN, DEPUTY UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ADVANCED TECHNOLOGY

DEPARTMENT OF DEFENSE
STATEMENT ON ROBOTICS TECHNOLOGY

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I. INTRODUCTION.

Mr. Chairman and Members of the Committee. I am especially pleased to have this opportunity to testify on behalf of the Department of Defense in order to present our views on robotics technology. This is the first time I have had the pleasure of addressing this committee. I would like to begin by briefly describing the role of the office of the Under Secretary of Defense for Research and Engineering in the field of robotics.

My office is responsible for what is commonly known as the "DoD Science and Technology Program." This includes basic research (6.1), exploratory development (6.2), and some advanced development (6.3A). Consequently, we are responsible for the technology base which includes robotics technology efforts within the Department of Defense. My colleague, Mr. William Long, the Deputy Under Secretary of Defense for Acquisition Management, is responsible for the industrial base applications of robotics.

We are particularly proud that early DoD investments have helped establish the basic scientific foundations upon which present U.S. capabilities in robotics and artificial intelligence are based. For example, the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) have been supporting research in the field of artificial intelligence for more than twenty years. ONR's early creation of robotic centers at Carnegie Mellon and MIT represents a major contribution to the Government and industrial robotics communities. These centers provide an invaluable service through their extensive publications and by hosting symposia and meetings for Government Agencies and industrial concerns. In the industrial arena, DoD funded the original development of numerically controlled machine tools which have now become an international industry. The basic technology utilized in these machines has provided the foundation for most current industrial robots.

II. RESPONSE TO QUESTIONS.

The major portion of my statement will respond to the specific questions provided by the Committee. It will become evident that the responses are from the DoD perspective and our mission needs. However, I will also address, where appropriate, our views on the overall context of the Federal Government's role in robotics technology.

1. What is the appropriate role for the U.S. Government in robotics research?

As a very basic premise, we believe that the Federal Government's role in robotics techology should be supportive and nurturing rather than directive and regulatory. This support can take many forms such as broadly based economic policies or direct funding to achieve specific goals and objectives.

The Nation's broad economic policies should focus on creating a sound economy and healthy environment which will provide the necessary incentives for the private sector to invest in capital equipment and new technology. Without a strong industrial base, we simply cannot maintain our standard of living nor, in DoD's case, can we maintain an adequate national defense.

In the specific case of robotics and robotics technology, we believe the Federal Government can provide support in five specific areas:

1) Basic research
2) Support of higher education,
3) Sharing of information,
4) Standardization, and
5) Mission related technology.

This list is in no particular priority order. I will comment in more detail on each of them.

1. Funding basic research: Robotics technology is not an isolated technology but rather an integration of a wide range of technologies and disciplines such as computer hardware, computer software, servos, actuators, and many types of sensors. Thus, much of the basic research sponsored by the Federal Government in many of these areas has supported and will continue to support the creation and formulation of the technological base for robotics and robotics technology, whether or not it is specifically identified as robotics technology.

2) Support of Higher Education: We see the role of the Federal Government in supporting higher education in two areas: a) to support centers of excellence in order to advance the robotics state-of-the-art; and b) to provide seed money or other incentives encouraging the academic community to create curricula which will produce the work force needed in a world of robotics. We envision that these would not be curricula of robotics, per se, but rather would include knowledge of robotics as one of the many skills that managers of the computer controlled factories of the future will need.

We recognize that it will probably be necessary to support both of these objectives simultaneously by providing funds for cadres of robotics experts who will conduct robotics research and simultaneously pass the knowledge gained to their students. We are in the final stages of selecting two universities to fulfill these roles. Our current plan is to fund each of them at about $1 million per year for four years.

3) Sharing of Information: Another potential role for the Federal Government is the establishment of a centralized means for sharing information. Let me illustrate by means of an example. Within the DoD community we have 20 Information Analysis Centers (IAC's). They serve as focal points for the various technological areas of interest to the DoD, to DoD contractors and to the private sector as well. Examples of the technical areas covered include: metal matrix composites; concrete technology; infrared technology; and plastics technology. The IAC's are similar in operation but dissimilar in subject. Each collects, reviews, analyzes, appraises, summarizes and stores information in its specific narrow technical area. The collections are expanded on a continuing basis to incorporate the most current information available. In addition, they often provide administrative assistance to DoD committees in their respective technical areas and promote the exchange of technical information by distribution of summary information.

The Federal Government could establish such a center for the distribution and diffusion of robotics information. Such a center would maintain active liaison with each of the interested Government Agencies and with the private sector, and collect information on current robotics investments and future plans. Abstracts of this information would be in a computerized data base which could be made available to the industrial base via dial-up computer networks.

Within DoD we have discussed establishing such a center for robotics but have not yet established one because we do not feel that robotics, per se, warrants it at this time. However, our FY 1983 budget request does include funds to establish an IAC for Manufacturing Technology and it is expected that robotics would be one of the areas of initial focus within that particular center. In fact, our current thinking is that it will focus on the more generic field of Computer Aided Manufacturing, of which industrial robotics is a subset.

4) Standardization: The Government has traditionally provided a leadership role in voluntary standardization programs for U.S. industry. It should continue this role in the robotics field. Industry wide standards are or will be needed in such areas as:

a) Safety;

b) Terminology;

c) Mechanical and electrical interfaces (end effectors, cable sizes, and pin functions, etc.);

d) Software, both internal to the robot itself (i.e., between various robot modules) and external to the robot (i.e., an interface to the environment and sophisticated sensors); and

e) Man-machine interfaces.

We believe Government's role must be one of a catalyst or a facilitator in establishing these standards. Some Government seed money may be needed to initiate these activities. We would look to the National Bureau of Standards to play a primary role but mission agencies, such as DoD, may initiate action in those areas where they see a pressing need and benefit to their specific requirements.

5) Mission essential technology: DoD has a very special responsibility in executing its national defense mission. Robotics technology has both military and industrial relevance. I use the term robotics in a far broader context than that of industrial robots. In this overall area we have three principal objectives:

a) To obtain whatever tactical advantages robotics may provide in executing military missions;

b) To avoid technological surprise by potential adversaries; and

c) To promote effectiveness, efficiency, and economy in the production of defense materials.

DoD's basic policy is to rely on the private sector for the production of its materiel. There are exceptions in those instances where there may be no commercial incentive (such as in the production of ammunition or tracked combat vehicles) or where the private sector is unable or unwilling to make timely investments to meet DoD's needs, either because there is no commercial market or because the resources necessary are beyond the scope of any one company to undertake.

A classic example of both situations occurred with the development of numerically controlled machine tools. The DoD needed these machines to cost effectively produce high performance aircraft and, as a consequence, provided sufficient funds to establish the technology and then incentivized the private sector to use them. DoD also provided leadership in developing the APT (Automatic Programmed Tools) language. The numerically controlled machine tool industry is now a worldwide activity and is an essential part of both the military and private sectors.

Today's situation with robotics is not quite analogous to numerically controlled machine tools, simply because a robot industry exists and the machines are being used in the industrial base. We believe a prudent way for the Government to accelerate the robotics industry, while simultaneously letting the free market system function, is by investing in applications of industrial robots where there is an opportunity to achieve a benefit to the Government from productivity improvements and/or cost reductions.

2. What is the nature of robotics research which is currently being conducted and/or funded by the Federal Government?

Robotics as a technology encompasses many disciplines, including computer science, artificial intelligence, optics, acoustics, mechanical engineering, and electronics engineering. Subcomponents of robotics technology have numerous applications in many mission areas such as: intelligence gathering, processing and analysis; operations planning; command and control; tactical warfare; targeting; fly-by-wire; logistics; and production of materiel. It would be extremely difficult, therefore, to identify every

DoD activity that has a bearing on robotics. Further, you should also appreciate that items such as image processors and sensors used in weapons guidance and targeting, although not classified as robotics, per se, bear a strong relationship to robotic vision systems.

Thus, although there are many disciplines involved and many of the things we do relate to robotics applications, I shall confine myself to our programs which deal directly with the subjects categorized as robotics and artificial intelligence. A summary of the robotics programs supported by the Military Departments is provided in Figure 1; as indicated, we distinguish between those elements which are funded from the R&D appropriation (Science and Technology) and those from the Procurement appropriation (Industrial Base).

Funding Summary -- Department of Defense Support for Robotics Technology

	($ in Millions)	
	FY82	FY83
Science & Technology (RDT&E Categories 6.1/6.2/6.3A)		
Army	4.8	11.0
Navy	9.7	10.0
Air Force	2.5	4.5
Defense Advanced Research Projects Agency	0.9	2.1
Sub-Total	17.9	27.6
Industrial Base (Procurement -- Manufacturing Technology)		
Army	1.9	2.8
Navy	1.9	7.9
Air Force	5.0*	5.7*
Sub-Total	8.8	16.4
Total	26.7	44.0

*Includes approximately $4.0 million per year of robotics efforts included in projects such as blade inspection and repair, composites manufacturing flexible machining systems, and plasma spray coating.

Figure 1

Science and Technology Programs in Robotics. The purpose of the science and technology programs in robotics and artificial intelligence is to develop and extend fundamental scientific knowledge and theory to support systems development and applications.

The objectives of our R&D funded activities are:

- Create centers of excellence at leading universities and research centers to address fundamental scientific issues and higher education needs;
- Create an in-house laboratory capability to develop and control special purpose military robotics and classified applications;
- Maintain DoD/university/industry coordination and cooperation; and
- Develop prototype hardware and software to support systems development and end-use applications.

The fundamental scientific issues under investigation may be summarized as follows:

- Robotics
    - Spatial reasoning
    - Image understanding
    - Control and stability theory
    - Computational strategies and architectures

- Artificial Intelligence
  - Knowledge representation
  - Knowledge acquisition
  - Machine reasoning
  - Machine adaptation
  - Language and graphics understanding

We currently have the following prototype hardware/software under development:

- Robotics
  - Advanced hand/eye/arm manipulators
  - Microelectronics devices and control algorithms for multiple cooperative robots working on a single task
  - 3D vision sensors and image processing
  - Stereo vision sensors and image processing
  - Acoustic sensors and wave form processing
  - Autonomous/semi-autonomous navigation systems
  - Mobile platforms and power sources
  - Survivability and control under adverse conditions

- Artificial Intelligence
    - Crisis warning and alerting systems
    - Situation assessment systems
    - Natural (English) language understanding
    - Expert systems
    - Automated computer programming
    - Automated mission planning and scheduling

Specific mission area applications of our systems-related research and development includes the following:

- Reconnaissance and surveillance
- Battlefield weapons systems
- Naval mine detection and clearance
- Land mine detection and clearance
- Deep diving salvage and recovery
- Material handling systems
- Manufacturing systems
- Command and control systems
- Inspection and maintenance systems
- Weapons delivery systems

Industrial Base Programs in Robotics. A key ingredient of our industrial base effort is the Manufacturing Technology Program (MTP). Its purpose is to improve the productivity and responsiveness of the industrial base by investing in advanced manufacturing technology of benefit to DoD.

It invests seed money in first-case applications of new technology; and because the results are made available to the industrial base, the MTP reduces both the technical and financial risks of follow-on applications by the private sector. The program also invests in areas where the resources required may go beyond the resources of a single company or industry--such as in the establishment of a higher order robot programming language.

The Manufacturing Technology Program includes both advanced technological feasibility demonstrations and production line demonstrations of first-case/prototype technology or equipment. These investments are pursued on a cost effectiveness basis where potential reductions in weapons systems acquisition costs justify dollar expenditures, or where the resolution of critical manufacturing problems clears the way to fielding improved combat systems. Specific objectives include:

- Development of innovative methods of manufacturing
- Demonstration of technical feasibility in prototype hardware/software
- Transition of successful advanced technology demonstrations to production
- Transfer of technology to universities, other laboratories and industries

- Demonstration of production line suitability
- Implementation of improved technology in the manufacturing of defense materiel

Currently robotic engineering problems being addressed by the MTP include:

- Machine control language
- Off-line programming
- Heuristic programming (teach-by-showing and teach-by-doing)
- Vision integration with robot control
- CAD/CAM data base programming
- Mobility/portability of robots
- Work station simulation
- Materials handling systems
- End-effector interfaces

Finally, robotic applications being addressed by the MTP are as follows:

- Grit blasting and painting
- Wire harness assembly
- Vision-assisted arc welding
- Materials handling
- Machine tool loading and unloading
- Grinding and polishing
- Plasma arc cutting
- Deburring/benching of metals

3. What long-range research needs to be funded by the Federal Government to insure US competitiveness in robotics technology?

The Department of Defense is interested in the application of robotics to battlefield missions and to automated flexible manufacturing and maintenance of weapons systems. The long range research needed to support these applications can be clustered in three scientific disciplines: a) computer science; b) mechanical and industrial engineering; and c) electronics.

The computer science research topics are shown in Figure 2. They include the development of: languages for controlling robots; automatic input of robot programming data from design data bases; special algorithms for control of robotic joints; and overall system integration of robots into systems of machines such as in a factory. One large class of topics is the research area called artificial intelligence (AI). AI attempts to use computers to perform human-like reasoning for tasks such as object recognition, speech recognition, learning from experience, and taking alternative courses of action when problems arise.

COMPUTER SCIENCE/ARTIFICIAL INTELLIGENCE

- High order robot languages
- Knowledge representation
- Geometric data base structures
- Computation geometrics
- Recognition of shapes and surfaces
- Special control algorithms
- Adaptive learning
- System integration
- Speech recognition
- Vision

Figure 2

The mechanical and industrial engineering topics in Figure 3 address areas such as means for increasing the speed of robots, improving their accuracy, and providing them with hands or grippers that can perform a wide variety of tasks. Improvements are sought in the control of flexible robots through adaptive control strategies that react to data from environmental sensors (e.g., vision, tactile, ultrasonic, etc.).

MECHANICAL/INDUSTRIAL ENGINEERING

- Structural dynamics and control
- Adaptive feedback techiques
- Flexible robot arms
- Sensor guided control
- Force/pressure sensors
- Grippers design
- Proximity sensors
- Accuracy
- Electro mechanical actuators

Figure 3

The electronics research topics in Figure 4 focus on improving computational hardware and on electronic sensors to enable the robot to interpret its environment. This research includes such things as microprocessors tailored to perform calculations for control of robot motion, low cost memory systems to store manufacturing data in the robot's memory, vision modules, and distance measuring sensors.

ELECTRONICS

- Computational hardware
- Fast microprocessor
- Large, cheap memory
- Vision sensors
- Tactile sensors
- Custom VLSI processors
- System integration

Figure 4

4. What efforts are being made to coordinate Federal robotics research?

Widespread interest and focus on robotics and robotics technology is a contemporary phenomenon. In reality, there is only a relatively small number of individuals in the Government involved in various aspects of technology specifically indentified as being related to robotics. Many of these people know each other personally. The informal inter-agency coordination takes place on an ad hoc individual-to-individual basis or through participation in various Government and private sector robotic activities. As far as budgeting for robotics research, DoD has not singled out robotics for special emphasis. Instead, the review of proposed robotics related investments takes place as an integral part of the normal DoD budget formulation and review process.

One example of this internal coordination occurs in the DoD Manufacturing Technology Program (MTP). Potential Manufacturing Techology Program robotic investments are reviewed each year by the tri-Service members of the Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) sub-committee of the DoD Manufacturing Technology Advisory Group (MTAG). Their review not only avoids potential, unnecessary duplication of effort but also provides a means of diffusing information on current activities (including that on robotics) among the DoD Manufacturing Technology Program community. Certain members of this group are particularly active in Government and private sector robotic activities and have a very good perspective of what is being funded by other organizations as far as industrial applications of robotics is concerned. For example, several of them maintain an active dialogue and work cooperatively with the robotics community of the National Bureau of Standards. The CAD/CAM subcommittee also maintains active liaison with similar committees in six industrial societies/associations.

The Office of Naval Research, to cite another specific example, has also been an active catalyst in coordination activities; they conducted a series of artificial intelligence seminars over an 18-month period and have been very active in funding seminars and workshops on robotics.

5. Should a national plan be developed to promote robotics technology?

This question can be addressed in two ways:

a) Should a national plan be established to encourage the use of robotics and robotics technology in the industrial base? or

b) Should a comprehensive national plan be established to advance the state-of-the-art in robotics and robotics technology?

We are not certain that either approach would serve to facilitate meaningful advances in robotics technology. In case a), we believe the Government should rely on the incentives of the free enterprise system to encourage the use of robots in the industrial base where there is an economically sound reason to do so. Robots should not be installed simply because someone considers it fashionable to do so.

We also question the feasibility a national plan as suggested by case b) -- especially if it carries with it the implication of a top down, centrally managed, interdepartmental allocation of resources. The missions, functions and scope of the various

Government agencies and Departments involved are so highly diverse (let alone the special interests of the private sector) that central planning and/or control, in our opinion, is neither realistic nor viable. It would probably consume more resources than could ever be saved.

As an alternative to national planning and control, we would prefer voluntary information sharing and participation in national interest activities such as standardization in the various areas of robotics (as discussed under Question Number 1 above). Such activities would be beneficial to both the private sector and Government Agencies. Voluntary participation would permit those who wish to pool their resources by cooperative efforts to do so, while also permitting those who wish to work alone to do so also.

Some may suggest that unnecessary duplication of effort would result. In our opinion, neither the private sector nor Government personnel want to unnecessarily duplicate efforts since there are never enough funds for all the opportunities available. However, unnecessary duplication can result when investment information is not being shared. Establishment of an information exchange system using today's computer data base technology is a viable approach to this coordination issue.

We also believe there are some merits to Government-sponsored efforts to establish a biennial robotic technological assessment which identifies, characterizes and quantifies robotics research and technical needs across the entire spectrum of technologies involved.

As indicated earlier, the most important role the Government can play in the overall coordination of national robotic efforts is to serve as a facilitator, a catalyst, or an umbrella for voluntary joint efforts among Government agencies, industry, and the academic community. The thrust of this role would be to foster national needs not just those of special interest groups. The entire standardization spectrum falls withing this concept. We believe such actions would be far more beneficial than an attempt to create a national plan.

III. CONCLUDING REMARKS.

It is apparent that the advancement of the state-of-the-art and application of robotics and related technology is important to the future of the Nation and to DoD's ability to provide for national defense needs. We appreciate the interest and concerns shown by the Committee in bringing together a highly diverse cross section of Government and other representatives to address this important topic. I am pleased to have had the opportunity to provide DoD input to your deliberations.

Mr. GORE. Thank you. That was excellent testimony.

Our final witness is Dr. Frederick Weingarten, representing the Office of Technology Assessment as Program Manager for Communications and Information Technology. Dr. Weingarten, welcome. Please proceed.

STATEMENT OF DR. FREDERICK WEINGARTEN, PROGRAM MANAGER FOR COMMUNICATIONS AND INFORMATION TECHNOLOGIES, OFFICE OF TECHNOLOGY ASSESSMENT

Dr. WEINGARTEN. Thank you, Mr. Chairman.

I would like to summarize my written comments.

Mr. GORE. That will be fine.

Dr. WEINGARTEN. My first comments will provide background information on our testimony. In October 1981 we published a report entitled "Computer-Based National Information Systems," in which we attempted to provide for Congress a broad overview of the kinds of information policy issues we thought that they would be addressing over the next decade. One of the major issues that we highlighted in that report, in fact, was automation and productivity in all sectors of the U.S. economy. Therefore, we certainly concur with the importance of this issue.

A report that we are currently wrapping up might be referred to as "Education In An Information Age." We are looking at the effects of rapidly burgeoning technology on education and training needs in American society and the reverse side of that coin, which is how this technology can be used, to improve that education and training.

More directly related to the robotics issue, we held a workshop last July because we sensed a growing congressional interest in the question. The workshop comprised a preliminary investigation of the state of the technology and what the issues were that might be of interest to Congress.

Based on the workshop report, the Technology Assessment Board in March approved a major study that we have just started. It will look at automation in manufacturing. The technology definition we have taken in that study is much broader than robotics, but it is focused on manufacturing applications and particularly employment impacts. We are looking at the effects on the workplace. We would certainly be pleased to keep your staff informed as that study progresses. The first panel meeting was held on June 2 and we will be having a series of workshops and panel meetings throughout the course of the study.

Our testimony, probably because we are at the start of this study, raises more questions than it answers. In some ways, also, I think that this is more in the OTA style. Therefore, I would like to start out by addressing those areas in which we think there is a lack of good information to make good policy in this area currently.

In the first place, we do not have a good picture of the overall state of research and development, particularly in the computer and communications technologies in the United States. We pointed that out a week or two ago in testimony on the impact of deregulation on Bell Labs. The United States seems to lack an overall information policy in the sense of understanding how technology is progressing, where the research is done, who is doing it, who is funding it.

We also find a difference of opinion among our advisers between the needs for research and development in what we call the hard technology—how to build the gadgets that make things—and what is called the soft technology—how to manage innovation, how to manage the transfer of technology from the laboratory to the factory floor, problems of human-machine interface, and so on.

We do not feel that we understand as well as we should the state of foreign research. A lot of the information that we have is anecdotal: People we talk to who have traveled to foreign countries come back saying, well, they saw what they were allowed to see, and so you really cannot form a judgment.

We do not know the effects of current changes in Federal policy taxes, and so on, on research and development, on the amount of basic research or long-term research that will be done in industry or the rate at which these new technologies will be adopted.

Finally, if one were to adopt a major technological thrust in this area for research and development, whether such a program would founder for lack of qualified researchers; whether it would draw researchers from other, equally vital areas of computer science or engineering; and so on.

At any rate, even given those unknowns, to address the question of a major Federal program in the area of robotics or automated manufacturing we identified six issues that we thought should be addressed in any such decision. The first issue was: How broad should that research be? Virtually every adviser that has talked to OTA on this issue has said that it is beyond robotics, and I think everybody else on the panel has more or less concurred with that.

Should it be basic or applied research? Well, aside from certain mission agencies such as DOD that have very specific needs for particular kinds of hardware, which will, in fact, devote their attention to development, basic research in the first place is a clear function for the Federal Government. Second, there is adequate capital to fund the development in the private sector of the next generation computer but the real issue is next generation plus one, the longer term.

I think I also want to draw attention to the problems of coordinating any such program between Government, industry, and academia. Those channels of coordination are right now very informal. They appear to be growing, spurred partly by the professional societies, but they are still in an uncertain state.

Another point that was brought up by one of my staff members that I found was particularly important was the relationship of such a research and development program with industrial policy—we do not have such a thing as an industrial policy. At the same time, the choices about the kinds of research to be done in this area can in fact implicitly choose or set industrial policy. We have heard that the National Bureau of Standards, for instance, has consciously chosen to focus on small-batch manufacturing. Other kinds of research and development could be of more applicability to automobile manufacturers or steel manufacturers. They all have different kinds of needs and a research program could, deliberately or inadvertently, focus Federal attention on one or the other.

Finally, there is the question of specific areas of research. We think that experience with the National Science Foundation and the National Institutes of Health indicates that in fact the Federal research agencies really do a pretty good job of setting specific priorities once they are given a general set of goals by Congress.

I would like to emphasize, though, three particular areas that may get left out. One is the soft technology that I mentioned earlier. Two is the area of social impacts. I think we have grown mature enough as a society to understand that when we have crash programs to develop technologies, we need to at the same time study the societal and economic effects of those technologies were they to be implemented widely. There is certainly reason to believe that automation will radically transform the American economy, the way we work, and so on.

Finally, we may not lose sight of the potential contribution of what I call "the science of the science," the very basic research. There are suggestions that the principal bottleneck will be in the software development and research directed to improving the productivity, using the technology, in fact, to increase the productivity of programmers and software developers may have a great deal of leverage.

This concludes my summary, Mr. Chairman.

[The prepared statement of Dr. Weingarten follows:]

TESTIMONY OF FREDERICK WEINGARTEN
MANAGER, COMMUNICATION & INFORMATION TECHNOLOGIES PROGRAM,
OFFICE OF TECHNOLOGY ASSESSMENT
BEFORE THE COMMITTEE ON SCIENCE & TECHNOLOGY
SUBCOMMITTEE ON INVESTIGATIONS & OVERSIGHT
U. S. HOUSE OF REPRESENTATIVES
JUNE 23, 1982

Manufacturing Research and Development

I am pleased to be here this morning to discuss issues pertaining to a special Federal research and development effort in robotics, or, more broadly, in manufacturing technologies. The general area of automation, its needs and impacts, is one where there currently appear to be more questions than answers, questions that become apparent when you start studying specific technologies and technology groups. Hence, in my remarks today, I will use my testimony as an opportunity to raise questions. First, however, I would like to start by reviewing past and ongoing work at OTA that informs my remarks today.

The Communications and Information Technologies program at OTA has been studing the development, application, and impacts of information technologies in a wide range of contexts. While these efforts have been channeled through separate assessments, they have shown that the impacts of information and communication technologies tend to spill over into areas beyond the focus of study, indicating the perils of an overly narrow focus on any one application or any one type of economic activity. Recent and current examinations of information technology relevant to the Committee's interests include the following:

Computer-Based National Information Systems (NIS): This assessment, the first to be published in the general area of information policy, overviewed a number of information policy areas that were likely to confront Congress over the next decade. Automation--and its potential for productivity improvement and employment impacts--was one major issue discussed.

Information Technology and Education: In the Information Technology and Education assessment, now nearing completion, OTA has looked at present and potential impacts of the computer, satellite, videodisc and other technologies on the design and delivery of educational services, as well as the existing research and development (R&D) climate for educational technology. Preliminary findings indicate that utilization of these technologies to date has changed the basic definition of education, in terms of who delivers it, when, and where. Preliminary findings also suggest policy questions regarding incentives for use of, and equity in access to, technology utilized in publicly funded education programs; support of research and product development targeted to specific educational needs; and other issues.

Exploratory Workshop on the Social Impacts of Robotics: This workshop, held last July, marked the beginning of the CIT program's investigation of the application of information technologies to manufacturing activities. It served to identify the principal technological, economic, and social issues pertaining to robotics. Participants debated several topics, most notably: (1) the development and application of robotics technology; (2) the structure and competitive conduct of industries producing robots; (3) international competition in the development, production, and use of robots; and (4) labor force implications of robotics.

A principal conclusion of the workshop discussions was that robotics is only one part of the spectrum of programmable automation technologies that is being introduced into manufacturing. Although some manufacturers may install robots alone, many manufacturers are expected to combine robots with computer aided design and manufacturing (CAD/CAM) systems and other instances of programmable automation. Consequently, it is, and will increasingly be, difficult to identify economic and, in particular, social impacts of robotics alone.

Information Technology, Automation, and the Workplace: The Information Technology, Automation, and the Workplace assessment was approved by the Technology Assessment Board in March. It will focus on manufacturing applications, encompassing the use of programmable automation in all stages of the manufacturing process, from product and process design through product delivery and servicing.

This assessment has several components. It will examine the state of the art and projected trends in robotics, CAD/CAM, automated storage and retrieval systems, and related technologies. It will characterize the current and projected structure, competitive conduct--with reference to international competition in both domestic and foreign markets, and financial performance of the industries producing programmable automation, and it will evaluate the impacts of programmable automation on the organization of industries using it. Most importantly, the Automation and the Workplace assessment will explore the implications of the production and use of programmable automation for labor and for American educational activities. Toward these ends, it will evaluate likely changes in the demand for different skills and occupations, the possibilities for unemployment and/or displacement of workers, potential changes in working conditions, and impacts on labor-management relations.

Finally, given anticipated changes in the numbers and types of personnel employed in manufacturing, relative to other sectors of the economy, the assessment will evaluate the adequacy of current and anticipated education and training activities, needs for specific new types of education and training, needs for retraining of current workers, and the coordination between academic, industry, labor, and other providers of education and training.

Although we are just beginning our exploration of information technology in manufacturing, we have identified several areas where we must expand our understanding in order to provide analysis that will inform good policy. I would like to highlight some of those areas for you that particularly pertain to the questions of interest to your Subcommittee this morning.

The state of industry R&D: While we know that industry support for and performance of all types of R&D activities now surpasses Government support and performance of R&D, we do not have a good understanding of the state of industry R&D in many specific areas of technology, including computers and communications and also more fundamental engineering areas, such as mechanical systems, tribology (the study of friction and lubrication) and materials, as well as controls, sensors, and actuators. Our knowledge of the state of basic or long-term applied research in these areas is particularly lacking.

We also do not know the effects of Federal R&D support on industries which are, or might want to be, involved in the development of manufacturing technologies. Projections for 1982 show, for example, that 74% of the R&D taking place in the aerospace industry and 41% of all R&D undertaken within the electrical machinery/communications industry will be funded by the federal government, with defense agencies providing the largest proportion of funds. We do not know how much of this support is targeted to basic or applied research in programmable automation. Moreover, we do not know whether this support effectively discourages innovation in similar technologies by firms and industries lacking the benefit of government support. It is possible that the presence or absence of government funding will determine which firms, in which industries, supply programmable automation.

There are several reasons to be concerned about industry commitment to basic research: For example, growing competition in domestic and world product markets may force companies to focus more than ever on relatively short-term, applied research, in order to meet near-term competition in markets for programmable automation and other products based on information technology. These efforts, however, may leave companies ill prepared to meet future competition.

Hard vs. Soft Technology: The relationship between "hard" technologies such as robotics and "soft" technologies pertaining to the implementation and management of innovation is poorly understood. Some industry analysts have observed that the United States has more manufacturing technology than it knows how to use, while Japan has done more than the U.S. to profit from existing levels of technology. Evidently, the process of technology transfer depends on how technologies are introduced and used, as well as in what directions technologies are developed. We need to know more about the interrelation between hardware and software systems development, facility layout, product design, and, in particular, the integration of human beings with equipment in order to gain the fullest improvements in productivity possible from new manufacturing technologies.

Foreign research structures: Our appreciation of our competitive position in domestic and world/foreign markets is hampered by a poor understanding of how U.S. research efforts compare with those abroad. In general, our information about the extent and quality of foreign research programs is anecdotal, at best. For example, it is conventional wisdom that the Japanese are better at applied than basic research in information technologies, but we have no unambiguous indication that this is indeed the case. We do know that many foreign countries--for example, Norway, Germany, and England--have a more organized approach to research than we do, making use of government-sponsored research institutions. We also hear a lot about concerted "national thrusts" in technology development, but we cannot always discern the real nature of government support behind the rhetoric.

Any judgments about the desirability of a foreign approach as a model for the United States should be based on an appreciation of why particular foreign research institutions have been effective; of the relationships between successful research institutions and industry, government, academia, and other aspects of society; of the scope of research that can reasonably be undertaken and encouraged by such institutions singly or collectively; and of the contrasts between the socioeconomic contexts of the U.S. and foreign nations. We lack satisfactory appreciation of these issues at this time.

- Federal policy: We do not know how recent Federal policy initiatives will affect the level and conduct of basic research. For example, we do not know the effects on industry's willingness to invest in basic research of reductions in Federal funding, changes in Federal tax laws and tax cuts, deregulation, apparent relaxation of antitrust restrictions, and monetary policies. While we have all speculated about the impacts of specific changes in Federal policy, it is impossible to say with assurance how these changes, individually and collectively, affect R&D. Our appreciation of the effects of Federal policy changes on R&D is especially clouded today since the recession that has accompanied these changes has interfered with normal business planning.

Manpower: There is substantial uncertainty regarding the status of research manpower--the numbers of current researchers and their distribution among science and engineering subdisciplines in computer- and communications-related fields, the numbers of current and prospective students entering into relevant research careers, the number and distribution by discipline of faculty, and the quality of training of both prospective and existing researchers. Most uncertain appears to be the adequacy of the supply of appropriate research manpower to the civilian industrial sector and to the education sector, since defense contractors appear to attract sizable numbers of scientists and engineers through offers of relatively high salaries and state-of-the-art facilities and challenges.

In 1980, over one-third of the universities most heavily involved in engineering R&D experienced such severe shortages in teaching and research positions that they were forced to reduce faculty involvement in research. Over half of these schools also found it necessary to curtail expansion of programs and course offerings to reflect the latest technological advances. Circumstances such as these are the motivation for national concern about the status of research manpower and the capacities we may have to develop such human resources in the long-term, regardless of fluctuations in manpower demand.

Many analysts maintain that a current and/or anticipated shortage of research manpower presents a crisis situation. They note that mere counts of students (and faculty) in relevant disciplines is misleading because of the substantial enrollment of foreign national students, especially in graduate training. Because engineering, in particular, has historically been sensitive to cycles in demand and supply of personnel, because basic training in engineering facilitates retraining and redirecting of practioners, and because certain engineering activities are themselves being automated, it is difficult to assess with reliability the extent of a possible shortage.

Questions for Policy

As I have indicated, there are many important issues regarding manufacturing technology research activity that require further study. Nevertheless, given what we now know about the state of manufacturing technologies, changes in industrial structure and competition, and R&D activities, and given our ability to identify areas to be explored, it is possible to raise several questions that must be answered in contemplating Federal policy relating to manufacturing research and development. These include the following:

If the Federal government should undertake a special R&D promotion program, how broad should its scope be?

Clearly, robotics is too limited. Both our workshop participants and advisory panel members have expressed the view that the scope of manufacturing R&D should be relatively broad, encompassing the whole range of component programmable automation technologies such as robotics, CAD, and CAM, and addressing directly the technological problems associated with integrating these components into systems.

Insofar as the potential for integrating manufacturing equipment stems from the ability to transmit data between equipment and systems and to process data within equipment and systems, research in computer science, programming, and process controls appears to be critical. Insofar as enhanced manufacturing productivity depends on more efficient mechanization and better product quality, research into materials, cutting and forming, process controls, sensors and actuators, and basic system mechanics appears to be necessary. Perfection of robotics technology, and technology for other instances of programmable automation, depends on research in these basic areas. It therefore appears to be unwise, or at least premature, to focus research exclusively on narrow aplication areas such as robotics, per se. Although, at the level of basic research, related technologies appear to blend together, it is at the level of basic research that yet new application areas may emerge, perhaps superceding those we now know, and that concepts for fully integrating systems can be developed.

Should the Federal government focus on basic research?

Proponents of government involvement in R&D generally agree that government efforts and funds are generally best spent on basic, rather than short-term applied, research. This is because industry tends to underinvest in basic research because such investment is relatively risky, and because support of applied research is often tantamount to support of specific products, implying choices that the government is not necessarily well equipped to make.

The appropriate level of government support for basic R&D, and therefore the balance between basic and more applied research supported by government, will depend on the willingness and ability of industry to sustain basic research efforts, an area where we have already acknowledged uncertainty.

Does a successful effort to promote a particular field of information technology research--say, automation--depend on the existence of policy and infrastructure for developing information and communications technologies in general? And, is one aspect of this policy base a human resource development policy that takes research manpower requirements and the need for periodic re-evaluation of same into account?

The mechanics of launching a successful effort to promote automation technologies (for example) depend on three main factors: the nature of existing and/or parallel efforts to promote information, communication, and other technologies in general; the adequacy of facilities; and the adequacy of appropriate manpower. Without strong, ongoing, and coherent policy support for the development of broad technology areas, it may be difficult to obtain quality research quickly in specific areas. It is reasonable to expect, for example, that if a crash automation (or, more broadly, manufacturing technology) research program were launched in the absence of appropriate infrastructure, obtaining the best manpower and therefore good results--return on the public's investment--quickly would be difficult or impossible. With limited or inconsistent policy support for information technology and other relevant research areas, there is no guarantee that adequate stocks of research manpower in computer sciences and industrial engineering, in particular, exist. Also, the quality and currency of research facilities is likely to be uneven.

Planning for programs to support manufacturing R&D should include investigation of the conditions of research facilities, the adequacy of research manpower, and the implications of existing manpower and facility conditions for research output. It should also consider the implication of research policy strategies for the maintentance of adequate facilities and manpower stocks for the future. Finally, I might also add that long-term planning should also address the need to assure that our population, especially our young people in or entering schools, is technologically literate, a point that has been raised in earlier testimony in front of this committee.

What provisions exist for coordination of R&D efforts?

Design of policy encouraging manufacturing R&D should include provisions for coordinating research efforts both in and out of the Federal government.

Within the Federal government, several programs to develop automation technology, for example, exist. The National Bureau of Standards, NASA, the Department of Defense, and other agencies sponsor or undertake research in the area of automation. Coordination of these programs would eliminate possible duplication and, more importantly, enable pooling of resources to support more the more intensive efforts that may be necessary for technological "leapfrogging".

Efficient use of material and human resources also would appear to dictate coordination of efforts between universities and other non-profit organizations, industry, and government. Government and industry have already, independently, begun to forge cooperative projects with universities. Emhart Corporation, for example, has established a Manufacturing Engineering Applications Center with Worcester Polytechnic Institute; Westinghouse has funded research at Carnegie-Mellon University; and Control Data Corporation has sponsored research at Purdue and elsewhere. Although joint industry-university programs are expected to become increasingly common, the conflict between university preference for basic research and autonomous intellectual activity, and industry preference for research relevant to specific manufacturing applications, may both limit the benefits from such programs and result in duplication of effort in programs sponsored by competing firms.

What provisions exist for technology transfer?

Mechanisms for technology transfer should be explored. There are several technology transfer issues that manufacturing R&D policy should address. First, there is the question of international technology transfer. Some observors believe that Americans are, in general, less aware than desireable of research published in Russian, Japanese, and possibly other foreign languages. Such "research isolationism" may result in inefficient and duplicative research activities in the U.S.

Second, there is the question of technology transfer between the military and civilian sectors in this country. The military sector has historically been responsible for many significant manufacturing technology developments. For example, CAM technology was launched in the United States in the 1950s with the backing of the military, which sponsored initial research and then made the use of numerically-controlled machine tools a requirement in certain defense contracts. While, as I mentioned earlier, defense contractors have the benefit of government funding to aid in pioneering new technologies, it may be desirable to facilitate the exposure of purely-civilian firms to new technologies to improve the productivity and competitiveness of civilian production.

Third, there is the question of access to new technologies by small businesses in both military and civilian production. There is already some concern, for example, that small suppliers to the aerospace industry are exiting from their markets in part because they lack the technical and financial resources to change their production technologies.

How does R&D policy relate to industrial policy?

The relationship between research and development policy and industrial policy should be examined. Programmable automation and other applications of information technology will affect the more mature industries in a different way than they will affect new, emerging industries. In designing programs to support R&D, the applicability of different technologies to different industries, the role of different industries in the economy, and the technologies and industries where the U.S. has (and doesn't have) competitive advantages should all be considered.

Directions for Research

I would like to conclude by listing some of the research topics that could fruitfully be pursued in the interests of improving manufacturing technology. Such a list is not terribly significant in itself. We have learned, through the experience of agencies such as NSF, NIH, NASA, etc., how to let the scientific and engineering community set specific priorities for research once Congress sets overall goals.

In the area of machine control and dynamic systems, areas for research include the design of adaptive, computer-based controllers for multivariable systems; dynamic coordination and optimization of interconnected systems; control system components, such as sensors and actuators; architecture and computational structures; and dynamic system modeling and simulation techniques.

In the area of tribology, areas for research include the characteristics of surfaces; perfection of seals and coatings; modelling of wear; and the potential for energy conservation through tribological developments.

In the area of machine dynamics, areas for research include simultaneous achievement of high-speed and precision; manipulator development; acoustics and vibration; measurement, diagnosis, and analytic techniques; development of modular system designs; and development of intelligent machines.

In the area of interactive computer graphics, areas for research include interactive, simulation-driven design and anlysis; computer anaimation of dynamic systems; computer architecture for design; geometric modeling and analysis; and computer language expansion.

Finally, research is also needed into a variety of social issues that arise with the development of programmable automation, including the nature and definition of man-machine interactions, which influence the compatibility of hardware and software designs with human users; the ways in which the introduction of programmable automation affects jobs; and the nature of changes in the type and mix of skills that accompany the use of programmable automation.

Mr. GORE. Thank you very much. That is interesting testimony. I want to thank all of you.

This is the Federal Government's work in robotics. There is nobody else that is not here that has a piece of the action, with the possible exception of a minor effort over at the Department of Energy. I think that this just about covers the waterfront. Does anybody disagree with that?

[No response.]

Mr. GORE. Well, the concerns of the subcommittee are several. By way of preface, let me say that I believe that you all are working on the cutting edge of a series of developments that are going to have profound impacts on our society. The accelerating scientific revolution that has so many impacts on all of our lives is popping out in this robotics area in a way that is going to change employment patterns as dramatically as did the industrial revolution, I believe, and over a much shorter period of time than was required for the industrial revolution.

The incentives to move forward quickly come not just from competitive pressures in this country but as a result of other nations having a coordinated and sophisticated program to exploit the potential of this new technology. The impacts on our society, the duty of the Government to catalyze job retraining efforts to mitigate the social impacts of this technology, make up another important concern of this subcommittee.

Let me ask first of all if anybody disagrees with that basic model of the problem: the enormous impact, the need to define where we are going, and what the implications of it are.

Dr. Lyons?

Dr. LYONS. I do not disagree, Mr. Chairman. I would like to make an observation. Before I came to the Federal Government, I worked for almost 20 years with a large chemical corporation, the Monsanto Co. Some of the things that are happening in the industries that we have been addressing today, which are really the batch manufacturing industries, happened or began to happen 20 years ago in the chemical industry. For example, the Monsanto Co. built the first computer-controlled chemical manufacturing plant 15 or 18 years ago.

Therefore, my comment and suggestion would be that some of these problems have been gone through and experienced by the chemical industry a long time ago. It just happens that making chemicals is a much more amenable process for automation than the kinds of things that we have been talking about. Therefore, there is something to be learned about the impact on labor by talking with the major chemical industries, those that are continuous processing industries. There is something to learn about the impact on productivity in the chemical industry. It was driven entirely by economic factors.

Therefore, I would like to suggest that the subcommittee or OTA or somebody might want to take a look at Du Pont, Monsanto, Dow, and the other giants in that business to see what lessons they have already learned because they are, by and large, fully automated already. I think in the current discussion about automation we tend to forget it. In fact, I forgot it until fairly recently when thinking about this hearing.

I also seem to recall about the same time, in the late fifties, there was a great concern then, particularly among the people interested in labor, about the impact of what they thought was coming in the late fifties and early sixties but in fact is only now beginning. Therefore, there was some pretty good thinking, I believe, that took place 20 years ago.

Mr. GORE. Well, that is a very useful suggestion and I appreciate it. We have had some testimony from the private sector, a good deal, but this suggestion of looking at the lessons learned in the chemical industry I think is a very useful one. If I am not mistaken, I think I remember reading that they are in the midst of a major transfer of processing, manufacturing facilities out of this country to other countries. Is that a tangential matter?

Dr. LYONS. Well, they have a different set of problems relating to feed stocks and energy but the one thing I do recall was, the impact clearly in the chemical plant was that instead of having people with picks and shovels and wheelbarrows, we switched to people who were expert in servicing sophisticated instrumentation, and that leads right into the training question because the level of sophistication was dramatically changed.

Mr. GORE. Yes. Well, that is an interesting, useful suggestion. Does anybody else on the panel quarrel with the basic model of the problem as I have presented it? Maybe it is not clear enough to challenge.

Yes, Dr. Albus?

Dr. ALBUS. I would suggest only that your comment that this would come much more rapidly than the first industrial revolution is probably true but that this technology is only in its infancy. Over the next 20 years there will be dramatic impact on manufacturing but it will go far beyond that. My feeling is that this technology will probably not mature for 50 or 100 or maybe 200 years and that these effects, dramatic though they may be in the next 10 or 20 years, will continue throughout the next century.

Mr. GORE. Well, while it may not mature for 50 years, we have a "Baby Huey" on our hands while it is in its infancy.

Dr. ALBUS. I absolutely agree with that.

Mr. GORE. Yes, Dr. Gevarter?

Dr. GEVARTER. I would like to second that. I think the Japanese program on the intelligent robot is largely geared for outside the manufacturing plant, so you do have it coming into various other portions of society.

I would also like to emphasize two things which were addressed by a couple of other people who testified today. One, DOD spoke about the importance of distributing information and this was reiterated by OTA but I think there are a couple of very important issues there.

One, the Japanese and others have systematically collected information, digested it, and distributed it in near realtime, which is something we do not do. There is a difference between information in undigested reports and information put into usable form so it can be utilized in near realtime. I think this is very critical.

My past experience with the defense industry was that we very often had to reinvent our information because it was much easier to reinvent it than to try to understand undigested information or even find it. I think, while we talk about the shortage of engineers and things of that sort, there is a tremendous impact on the fact that these people are all busy hunting up information, reinventing information, trying to find information.

Mr. **Gore**. Yes.

Dr. **Gevarter**. Off the top of my head, I would say you could almost double the impact of the engineers existing today if they could have information of the type they needed readily available in near realtime. Therefore, these are important impacts.

Mr. **Gore**. Yes.

Dr. **Gevarter**. There have been some estimates that perhaps 40 to 80 percent of the Japanese advance in the automation area has been due simply to gathering of intelligence, so these are very fundamental things and often overlooked. I think what you are doing today is gathering information, realizing the importance of the information content.

Mr. **Gore**. Yes. Our problem is what I call "exformation." It is outside of the integrated ability to process it and deal with it.

Well, let me move to the next step, then, if there is no serious disagreement with the subcommittee's perception of what the likely developments are.

The second step is what our goals as a country ought to be. I suppose there is an intermediate step: Should we set goals as a country? I think we should. If you get over that hurdle, the question of what the goals in this area should be, I think there are two and I want to invite all of you to agree or disagree as you wish—both of them controversial. No. 1, I think that we ought to have a much better coordinated and accelerated effort to develop and utilize the technology that is under discussion here in order to enhance the productivity of the United States and enhance the competitive position of the United States in world markets. The second and related goal should be a recognition by the country of a much heavier obligation to provide job retraining and skill acquistion for the millions of our citizens who want work but are currently trained in occupations that are diminishing in importance and value and do not have the skills that industry finds that it needs and is increasingly going to demand.

Now those two goals, it seems to me, ought to be the two principal goals of the country in this area. Does anybody want to comment on that?

Yes, Dr. Lehn?

Dr. **Lehn**. I agree with what you are saying. If I can back up just to sort of agree with Dr. Albus on the time frame here as to the implementation of this particular technology, the development of NC machines in the late fifties and then the application throughout the years——

Mr. **Gore**. NC's?

Dr. **Lehn**. Numerically controlled machine tools.

Mr. **Gore**. Oh, yes.

Dr. **Lehn**. This suggests that Jim is probably right, that it will not happen as fast as expected, and as we expected it years ago. I think there are about 4 percent, or something like that, of the machine tools in the United States right now that are NC machines, and we expected that this was going to be the second industrial revolution and it was going to happen overnight. It has not. We do not really quite understand why industry has not used as many NC machines as they potentially could.

This relates back to your second goal——

Mr. **Gore**. Let me stop you there and then invite you to proceed after this comment. It seems to me that with the NC machines you were at a level of control that required you to do an enormous amount of work and capital investment in order to match the machine to the task. With the software available now and the flexibility of modern robots, a single robot can be matched to hundreds of different tasks with changes merely in the software. It seems to me that increases exponentially the rate with which these machines are adapted to different tasks.

Dr. **Lehn**. Well, I think if you go back in the history of numerically controlled machine tools you will see at one point people believed that they would program those machines similar to the way we program robots primarily today, which is in the lead-through or teach mode. We tried that. We found in fact that we were putting the errors into the motion because we were machining and those errors would just repeat themselves, so it became a need to have higher order languages of some sort to program those machines effectively.

Today, the robots, most of them are led through. If we are going to use them, in my personal opinion, as much as people think that they will, we are going to have to develop the language in order to do this offline programing. Some of that programing is not trivial. It may take 20 or 30 hours to do a single part, and if you are on an aircraft where you have thousands of parts, that adds up. You do not really have the flexibility that you might envision but that can be worked out and that is the type of thing that I think we can do together.

Mr. **Gore**. Well, proceed with the response that you started to give.

Dr. **Lehn**. With the second goal, if in fact it is going to take, say 20 years, are we now generating a new society with, for example, the home computer revolution where the children who are growing up today are going to grow up in an environment of computers. They are going to accept this technology and we will have a work force trained at the level to use these machines.

Mr. **Gore**. All they know how to do is play Pac Man, most of them.

Dr. **Lehn**. I do not really think that. I think that they are going to evolve over a period of time. I have one at home. I have a 7-year-old. He is interested in Pac-Man. He is interested in other games, but he is also interested in saying, "Hey, I can make this machine do things." I think that is going to happen.

Mr. **Gore**. Well, my children are the same way but the majority of families do not have such opportunity and if you look, it is not really a question of moving toward such a society. We already have such a society. I mean, this is a more current issue and outside of what we have asked you to testify about but, seriously, today you see a very high unemployment rate due to the loss of jobs in traditional manufacturing areas, traditional skills. Then you look at the want ads and there is this incredible demand for programing and electrical engineering and all this stuff.

I mean, it has already started. Nissan is building a factory in my district that is going to be heavily robotized. We are grateful for the number of jobs that are going to be there, but the ratio of jobs to output is just incredibly low compared to what an old-line automotive factory used to be.

However, let me ask you on your response to the first goal, if you assume that the timeframe is going to be stretched out a little bit, you still have coordinated efforts in other countries that are apparently moving faster than our effort is. No matter what the timeframe is, whether it is 10 years or 20 years or 50 years, doesn't it make sense for us to respond to that challenge by better coordinating and accelerating our own effort in this area?

Dr. LEHN. Well, I think you could say on the surface, yes, but if you look at the free enterprise system I think that some of the figures that are published show about 150 robot companies in the country today that are in the competitive marketplace. They are going to sell these products, and if the industry sees productivity benefits from them, they will pick them up and use them as part of their competitive position within their industry and in order to survive.

Mr. GORE. However, can they do that when their foreign competitors are about to go to MITI, for example, or its counterpart in another country and get the kind of assistance that American industry will not have available to it?

Dr. SANDERSON. Congressman Gore?

Mr. GORE. Yes?

Dr. SANDERSON. I think it is important to keep a few things in perspective. While numerically controlled machines are only about 4 or 5 percent of the inventory of machine tools in this country, a much larger fraction of the U.S. productivity is already being handled by numerically controlled machines. Some figures say as much as 75 percent of our manufacturing is done on this 4 or 5 percent of machine tools which are numerically controlled.

Mr. GORE. Therefore, the lessons from that era may be cut both ways.

Dr. SANDERSON. I think the lessons cut both ways on that one. I think it is also important to realize, as several people have remarked, the United States has a great deal of strength in the diversity of its free enterprise and the free market systems. Yes, we do not have a Ministry of Trade and Industry [MITI], which one can go to and create organized and coherent programs. On the other hand, if the Nation decides that it is important for us to move ahead more rapidly in the introduction of robots and automated manufacturing, we need to explore ways that we can do it within the American system, using such alternatives as tax stimulants as well as public leadership. Certainly there is a major role for Government to play, not just Federal but State government, community governments, and industry itself in retraining workers. There are some studies which are still underway looking at the impact of technology on workers and the impact of various efforts to reduce the displeasure and the discomfort of workers at the introduction of new technology. Although job assurance has been a major factor in making workers amenable to accepting new technology, surprisingly, a much stronger factor has been clear and continuous communication between management, labor, and the people who are implementing the change. The workers in general are willing to take new technology if they have some assurance that they will not lose their jobs and if they are kept informed and get a chance to participate.

However, there are areas on which I think the Federal Government can take an important step in moving this technology forward. The first is, of course, in providing proper incentives to encourage capital formation. These tools are not cheap and the difficulty of putting together capital in a market where money is going for 17 to 20 percent is great.

Another area which clearly we are very concerned about is the scientific and technological base which underlies the introduction of much of this automated machinery. We have done, I believe, fairly well, perhaps very well compared to the rest of the world, in building some of the basic technological components, for example, some of our work on sensors. Clearly we are the world leader in computers at present.

We have not, perhaps, emphasized in our educational system or in our on-the-job development the necessary systems planning, that is the ability to conceive and develop entire automated manufacturing systems. The Japanese are capitalizing on this ability at present and they are gaining additional valuable experience by producing model automated factories, even if those factories do not prove over the long term to have been technologically a wise decision. Therefore, certainly some form of incentives for industry to take risks in this area, I think would be valuable.

Mr. GORE. Yes. We are the Encylopedia Britannica for the world. When they want to find something out, they know they can find it out here.

Dr. SANDERSON. However, there is a great power base in being the Encyclopedia Britannica.

Mr. GORE. If we use it.

Dr. SANDERSON. If you use it and its information to accomplish social goals.

Mr. GORE. That's right, but we are not using it very well. It seems to me we are not.

Dr. SANDERSON. I think I agree with you but I certainly get very nervous at the idea of talking about a U.S. equivalent of MITI or a planned society.

Mr. GORE. Your point is well taken and one I agree with, that whatever coordinated effort our country undertakes in this area should of course be adapted to the competitive, free market system that is our basic strength. However, coordination is not mutually exclusive with reliance on the free enterprise system.

Dr. Martin?

Dr. MARTIN. Yes. DOD spends 55 percent of its budget on personnel and training. We have a resource shortage. We do and we will retrain. We welcome robots, and we would like to buy American.

Mr. GORE. OK. [Laughter.]

Dr. MARTIN. How's that?

Mr. GORE. Very good.

Dr. **Sanderson**. Congressman Gore?

Mr. **Gore**. Yes.

Dr. **Sanderson**. I think one of the areas that Dr. Lyons emphasized could be an important contribution to the U.S. effort. I remember the experience we had with the computer industry in its infancy, when, thanks to a variety of reasons, we were dominated by a single large company. That company was very effective in setting standards for interfaces between computer components and developing standards for higher level languages, which they made readily available in terms of licensing to young computer startup companies.

As a result, the computer industry has always had a great deal of flexibility in plugging one manufacturer's disk into another manufacturer's mainframe. The problems have been minimized. I have not seen that occur as readily in the area of robotics and automated manufacturing, where there is a great deal more proprietary systems development. Therefore, the efforts of Dr. Lyons in trying to build standardized interfaces may in fact contribute a great deal toward the widespread adoption of these systems.

Mr. **Gore**. Yes, that sounded encouraging to me as well.

Yes?

Dr. **Martin**. However, the trend is there. You know, we do procure on a competitive basis, and if U.S. industry cannot be competitive with foreign suppliers in shipbuilding or fine-grade steel or robotics, then we will have to procure from foreign sources. Unless something is done, it is very likely that that trend will occur in this industry as well.

Mr. **Gore**. Dr. Albus?

Dr. **Albus**. Yes. I would like to suggest that your second goal, the notion of providing some sort of a guarantee or some sort of a social compact for job retraining, is very important. It seems to me that one of the reasons that the Japanese have been so successful is first off they came to a national consensus that this technology was good and, second, they have institutional mechanisms by which there is very little fear of unemployment as a result of increasing productivity through these machines.

Mr. **Gore**. Yes.

Dr. **Albus**. It seems to me that the technology would proceed a lot more rapidly in this country if the labor-management relationship had some sort of plan, or mechanism—certainly not a copy of what the Japanese have—but an American version of a social compact that guarantees that the wealth generated by these new machines and this new technology would be adequately and equitably distributed so as not to result in massive unemployment and dislocation.

Mr. **Gore**. Good luck. That is going to be hard in this country and it may devolve upon the Federal Government to provide such assurances that people who are displaced as a result of these developments have a right to job retraining and employment elsewhere.

Dr. **Albus**. I am not presuming to suggest that the Federal Government should guarantee employment or anything like that. What I am suggesting is that the notion of a social compact, where the average person feels that he has something to gain from the increased productivity of American industry, is very important.

Mr. **Gore**. Absolutely, and this came out at our last hearing quite a bit. There is the potential in this country for the American work force to develop a real hostility to this trend. I mean, it is not hard to find already but that would be a mistake because, to the extent we are behind the curve, other nations are going to take jobs away from the United States so it is a net loss. If we artificially impede this trend we suffer a net loss of jobs, not a gain.

Dr. **Albus**. The real threat to employment is by not implementing this sort of technology.

Mr. **Gore**. I have learned that from these hearings, or at least I think I have, but in order to make it possible for the United States to exploit this technology in rational way you have to have this social compact, or you have to give assurances to people in danger of losing their jobs that they are going to be able to work.

We are not doing that today. We are not doing that today.

Dr. Weingarten, you have been wanting to say something.

Dr. **Weingarten**. Yes. I wanted to return to your two points. On the first point, there is a fundamental problem with the transfer of technology to the factory floor. It is not so clear where that problem lies, whether it lies with management as Abernathy and Hayes from Harvard might suggest, or whether it lies with resistance from labor unions which we really, in the early parts of our studies, have not really found. In fact, according to the people I have talked to there seems to be more potential for a serious union reaction against office automation than against factory automation. It might be because the availability of capital. It might just be something in the way the smaller industries, in particular, are set up to adopt new technologies and new production processes.

We just do not know where that resistance is, but a lot of experts tell us that other countries manage it better and that we are paying a severe economic cost for somehow not managing that transfer better.

On the second issue, the need for retraining, we have already decided at this early stage in the project, in fact, that if there is a key pivotal issue in Federal policy, it is this question of retraining. It does not just stem from manufacturing automation. It stems from our moving into what people call an information society, in which the nature of our work is going to change on the average of every 5 to 10 years.

It requires a work force that in the first place is educated to be more flexible, so that this transfer can take place easily, and, second, we need processes and structures that take care of the retraining need. In fact, people have suggested ways of anticipating it so one does not wait until somebody has been thrown out of work before finding something else to teach them to do, but retrain them in new skills while in fact they are doing their old job.

Mr. **Gore**. I am prepared to move on, if anybody else wants to respond to this larger question of what the country's goals ought to be in this area.

Yes, Dr. Gevarter?

Dr. **Gevarter**. Yes, I would like to agree with OTA and some of the other statements here. We are at a point, when we would like to retrain these workers, the question is how long will retraining last. Essentially, it is not a matter of retraining, it is a matter of continuous training.

Interestingly enough, DOD I think probably does this better than anybody else. As a person is on one job, they are usually—often—taking courses for jobs downstream. I think this is something the United States has not yet accepted. You cannot become well trained for a job and have it last a lifetime. I think the OTA position is very realistic and it is part of what is happening. I am afraid that our manufacturing people are not giving adequate consideration to their workers, predicting the future and keeping their workers up to speed for what is coming next.

The other problem we have is that I think a good deal of our society finds education burdensome and in some way frightening because it also implies the possibility of failure. I think this is one of the things our schools have been suffering from as well, so I think you are touching very deep problems when you get into this problem of retraining.

Thank you.

Mr. GORE. Well, thank you very much.

Are any of the agencies represented here familiar with any attempt that has been made or that was started to devise a national plan for robotics or automatic technologies? Has there ever been such an effort? Dr. Lyons?

Dr. LYONS. We had talked about it 2 or 3 years ago in the Commerce Department. It never emerged as an official document. There was a lot of thought given to what the component parts ought to be of some sort of a national automation program.

Mr. GORE. That is interesting. There was no draft prepared?

Dr. LYONS. There was a draft submitted to the Secretary of Commerce. As far as I know, he never did anything with it. The tides of the budget changed—this was the summer of 1980—and so it has been in limbo for the last 2 years.

Mr. GORE. Several things went by the board, sir, in the summer of 1980. [Laughter.]

Mr. GORE. What were the key elements of that plan?

Dr. LYONS. Well, we talked about the technology needs, the hardware needs, a need for a different generation, perhaps, of machine tools and robots that could do things at higher speeds with more power, reliable sensors, the sorts of things I think have been discussed here. We talked a lot about software development. In fact, that comes up whether you are talking about automated manufacturing or computers in general but the costs of tomorrow are going to be 80 or 90 percent software and maybe 10 percent hardware, so we gave a lot of thought to better software and that is a precursor for some of the interface standards that I am talking about today. We talked about expert systems, expert computing systems and how you could adapt that kind of technology to robotics and to manufacturing and automation.

We talked a lot about online quality assurance, making measurements on the fly as you are doing the operation. We talked about reliability and redundancy, new technology instead of cutting, near-net shape technology, pressing and other kinds of shaping. We thought about technology transfer. We thought about things like the Agriculture Department's Extension Service, about whether or not one could do the same sort of thing with a small manufacturing shop. Indeed, the University of Maryland has since begun to do that, precisely that, in western Maryland. They have a technical extension service. Here is a case of a State responding to the need, a need for some place where a small businessman can go to learn about this technology without having to make an investment.

Now I understand the committee has thought some about leasing programs, and of course Japan has such a program. We were not thinking about that. The question was, If I am considering making a major investment in going to a flexible manufacturing system, where can I go to try out my product to see if such a system can make it, to get a fix on the profit and loss and the amount of assets I have to have?

We just thought about those things. I am not saying we have the answers.

Mr. GORE. That is OK.

Dr. LYONS. We also talked about a data bank. We talked some about that this morning, where the engineer can go to get access to evaluated and demonstrated information. It is not good enough to have an idea. Who has some ideas on a process that works? What was the validation process? Then this whole question of retraining of manpower, dealing with the current generation that is of middle age, and more importantly, I suppose the youngsters who are in school. That question is now being addressed by lots of people.

We talked about technical literacy in general of the school population, and we were and are very concerned about things like statistics and computers, and cost-effectiveness concepts. How do you get young people to think about cost effectiveness? How do you do problem analysis in this technological age? I suspect the way most of us do it today is pretty willy-nilly and not very effective.

These are some of the items that we kicked around in thinking about what the country ought to do. By the way, I wanted to say that on your two goals, I do not think that anybody would disagree with the goals. I think the issue in this city these days is how and who, not so much what.

Mr. GORE. Well, I think some might disagree with the first goal that there should be a coordinated effort to accelerate the development of the technology and the ability of the country to exploit it.

Dr. LYONS. It is a question of who coordinates. If you say that the industry ought to pull itself together and move out smartly, one does not have to assert that the Federal Government needs to spend money, for example, to accomplish the end. Maybe what is needed is a certain catalytic effect, the stimulus of hearings like this, the kinds of things that we are proposing to do which are really very deep in the infrastructure of technology. These things are crucial but they are not right in the application of making products.

Mr. GORE. I think that is well stated. It is my view that in a time when history is speeding up and the process of change is accelerating, and the stakes are much higher, then goal alinement among the disparate elements of a society as complex as ours becomes much more important. I hope you are right, that there is no serious disagreement with those twin goals because I think it is important for various parts of our society to move in that direction.

Do you have a copy of that draft? Do you think you could find one of those in one of those old dusty files over there?

Dr. LYONS. Well, we have bits and pieces of it. I am not sure I could find what the Secretary has. Let me ask. It was associated with the budget at one point so it is a little bit sensitive, and I will have to go back and ask what it is we could release.

Mr. GORE. Well, we will subpena it if you want us to. [Laughter.]

Dr. LYONS. This is supposed to be a friendly hearing. [Laughter.]

Mr. GORE. You just let us know if that is required because we would like to take a look at that.

Since it was associated with the budget, I wonder, were any funding levels—did you ever put a pencil to paper on what the cost of such a program might be?

Dr. LYONS. Well, we were talking in terms of the competition. The numbers that we had in front of us were that the West Germans were spending on the order of $100 million a year, and the Japanese had a national effort to spend $100 million a year, so we were trying to think of what the United States might do in the same ball park.

Mr. GORE. OK. That is in some contrast to what we are spending now. I have the relevant budget figures here and I think they are correct.

The National Science Foundation, Dr. Sanderson, has had $5 million in this area in fiscal year 1982. The figure in 1983 is, again, $5 million. In NASA it was $2 million in 1982 and $3 million in 1983. Correct? The National Bureau of Standards was $2.31 million in 1982 and that has gone down in 1983 to $1.895 million. Correct? Then we come to DOD, $26.7 million in 1982 and that has gone up $44 million in 1983. Is that correct? I know you get tired of this embarrassment of riches, Dr. Martin, but that does seem a little asymmetrical. Do you want to comment, or Dr. Lehn?

Dr. MARTIN. I am not sure what the question is. You would like to know why we are going to spend $26.7 million——

Mr. GORE. Well, let me ask the question a little bit more—and maybe you are not the person with the responsibility for answering the question. It is a variant of one that is asked in many forums and many contexts.

If we are going to have a coordinated approach, why would the Department of Defense have a program that is 10 times that of the rest of the Government combined?

Dr. MARTIN. Well, I cannot speak to the rest of the Government but I think as we look at our defense strategy, high technology is the cornerstone of our strategic plan, and that is that we anticipate using high technology as our force multiplier. What we see as an integral part of our new weapons systems are smart electronics, fire and forget, for example. What you see in these new weapons systems are really strange-looking robots, so what you see in the budget figures for 1982 and 1983 are actually only our 6.1 and 6.2 and 6.3A efforts in robotics and artificial intelligence——

Mr. GORE. I see.

Dr. MARTIN [continuing]. But we are actually applying this in real systems, and those systems have us, we feel, in a strategic lead over our adversaries. It is money very well spent.

Mr. GORE. Certainly the lessons of the Falklands and Lebanon would lead one to that conclusion.

Dr. MARTIN. Yes, and as I listened to the discussions that have gone on today, I feel that a similar commitment in the industrial arena would certainly benefit the commercial portion of the USA. It certainly has benefited us.

Mr. GORE. Yes, we are kind of in a strategic trade conflict with different countries, a friendly conflict, thank goodness, but one where the stakes are pretty high and one where we have not had the same concentrated effort that we have in the military arena, and I think that is evident from these budget figures. The response is an elegant one but the question, I think, remains to be—the answer will require more from others in the Government, not from you.

Yes?

Dr. MARTIN. Well, our mission is defense and this is what we feel is necessary in order to accomplish that mission. If we look at the Department of Commerce, and if I might be so bold as to say that their mission is the economic health of the country, then they might be equally ambitious in pursuing that.

Mr. GORE. Yes, I agree. I certainly do. [Laughter.]

I certainly do. You have made some friends here, Dr. Martin. [Laughter.]

That is very good.

Again, though, the numbers—Dr. Lyons' program has gone from a measley $2.3 to an even measlier $1.895, and the program over there has gone from $26.7 to $44. I think that you have reframed the question quite properly so that the question becomes not why is yours so large but why is theirs so small.

Dr. Lyons?

Dr. LYONS. Mr. Chairman, I cannot pass this up. We were asked that question by Mr. Walgren or Mr. Brown, I forget which. We assured him that we were going over to DOD to make up the difference.

Mr. GORE. Well, you will have to stand in line because there is a real effort to get programs labeled "national security" these days.

Well, we will look forward to getting that draft plan because we are going to be very interested in this.

Looking at the Japanese plan for a moment, there appear to be five elements in the Japanese plan: No. 1, a 7-year, $65 million plan to develop FMS or a flexible manufacturing system, an automated factory; the second element, a 7-year, $150 million program to improve research and development capabilities in robotics' the third element of the plan, the establishment of the Japanese Leasing Corporation which leases robots to companies; the fourth element in their plan, the Government provides low-interest loans to small- and medium-size firms in order to encourage the wider use of robots; the fifth element in the Japanese plan, an additional 13-percent depreciation on robots.

Now those five elements together present an awesome challenge to the United States in the exploitation of this technology. I would like to ask each of the institutions represented here if you would comment on the applicability of these provisions in the United States and any comment you want to make on the Japanese effort but, with your indulgence, we have another vote on the floor. The committee has a bill on the floor and, if you would indulge the subcommittee, we will have a break for about 8 or 9 minutes and then we will resume.

[Recess taken].

Mr. GORE. The subcommittee will come back to order.

I had just asked the question about the Japanese program which seems so impressive from a distance. If any of you have a reaction to the program and views on the applicability of the various elements of the program here in the United States, I would be interested in your responses.

Dr. Albus?

Dr. ALBUS. Yes. I had the opportunity to spend some time in Japan just last fall at a robot symposium and tour a number of robot installations. I know it is a common, perhaps chauvinistic notion that because this technology originated here in the United States, that we enjoy a big lead and the Japanese are just copying what we are doing. However, after seeing the line of commercial robots that are currently available on the Japanese market and reviewing some of the research that is going on in their laboratories, it appears to me that while we may still have a qualitative lead in a few areas, particularly in the advanced artificial intelligence areas and the computer science areas, that we no longer enjoy a lead in the mechanical structures and the quality of the robots that are actually being produced.

I think to some extent that is reflected in the fact that the major U.S. corporations that have just entered the robotics field have chosen to license foreign robots rather than domestic robots. For example, General Electric, General Motors, Westinghouse, and IBM have all chosen to launch themselves into robotics using foreign robots. The scope of this Japanese package, on top of the fact that they appear to have essentially drawn even coming from way back in the field, does not bode well for the future of our position in this technology.

Mr. GORE. Dr. Weingarten?

Dr. WEINGARTEN. Yes. I would like to comment a bit about the problems that might be inherent in looking too closely at a foreign program and adapting it to the United States. Even if our goals were consistent with the Japanese Government, the elements of that program are directed at what they see as their specific bottlenecks in their system, their economic system, their social system.

What that implies is that even if the United States decided to focus on, say, the manufacturing sector, on automating the manufacturing sector, the particular components of a program, the levels of funding, and so on, would be different. For instance, it is strictly a personal opinion and I certainly do not speak for OTA, but any U.S. program it seems to me would have to focus on manpower issues. The production of computer scientists and engineers has been level for 10 years. I just do not know where all these people are going to come from, even to cover that increase in spending that DOD is projecting for next year. Where are the high technology scientists and engineers going to come from just to cover that? Will they come from other areas of research that are equally important?

Therefore, I do not see how a U.S. program could avoid focusing on this general problem of education.

Mr. GORE. Education and retraining.

Dr. WEINGARTEN. Yes, general education for the population in technology literacy, and also the production of computer scientists, engineers, industrial engineers which we have also been told are in great shortage. That is a very important problem in the United States that perhaps the Japanese do not feel.

Mr. GORE. Yes. An organization with which I am associated, the Congressional Clearinghouse on the Future, recently conducted a computer literacy course for Members of Congress and we had a very interesting response to that. [Laughter.]

I agree with your comment but I am not sure I agree with your preface, that their program is designed to address the bottlenecks inside Japan. I had had the impression that their program was one with global goals, designed to position Japan to play the leading role in the manufacture and introduction of robots in a wide variety of industries around the world.

Dr. WEINGARTEN. Well, as I say, we could agree on the goals. The United States and Japan could have consistent goals but still have to have different elements of a program to achieve those goals. For instance, low-interest loans to small business: we have a difference of opinion on our advisory panel about the availability of capital to U.S. firms, about whether or not it is in fact a significant barrier to their adopting the technology. Other kinds of barriers have been mentioned as being more significant.

Mr. GORE. OK.

Dr. Larsen?

Dr. LARSEN. I would just like to start by reinforcing Dr. Weingarten's comment on computer science and reflect a little bit on the situation in Japan being one of an integrated effort, including academia as well as industry as well as government, which we are lacking. The impact is that in the short term our better people, particularly in the computer science departments, particularly focusing on artificial intelligence, are being drawn into industry simply because it is so rewarding monetarily.

Therefore, industry will reap a short-term benefit from that, maybe 5 years, and a long-term loss. Peter Denning, in "Communications of the ACM," I think in the February issue of this year, focused on that topic of the strong lack of people in computer science departments in universities, and that is where the long-term source of this support is going to come. At the present time we have a bit of a luxury in being world leaders in the area. You yourself, earlier in the proceedings, I think if I quote it appropriately, mentioned that robots can be adapted with changes, with emphasis now merely in the software.

It has been, I think, the experience of those of us in the computer science community that that word "merely" has come to haunt us many, many times, and that in the future probably the majority of our problems in robotics and the applications of artificial intelligence in factories are not going to be hardware oriented at all; they are going to be software oriented.

Therefore, my message is that a major ingredient of a long-term program has to be in the university computer science community which is now very poorly funded, to the point that those people are under severe pressure to go into industry and reap the short term benefits.

Mr. **Gore**. Yes. That comes under the heading of consumption of seed corn.

Dr. **Larsen**. Exactly.

Mr. **Gore**. Mr. Holcomb?

Mr. **Holcomb**. Yes. I would like to expand a little on Dr. Larsen's comment. The second point of the Japanese program is an aggressive, 7-year research and development investment. The understanding that we have of that element of the program is that it is targeted on the development of intelligent robots as a long-term objective. That that objective is one that we share with the Japanese, at least from the NASA perspective. We also feel that an important element of long-term research and development is the university programs to build strength in our future generation.

I would also like to extend a comment on another area which has to do with the approach to the transfer and utilization of advanced technology that is evolving out of the robotics area. We have a program which we call the Integrated Programs for Aerospace Vehicle Design, or IPAD. It has been underway for about 7 or 8 years now and it focuses on the issue of computer-aided design. This particular program was set up with about 58 companies acting as members of an industry technical advisor board to guide the technology program and assure its utilization.

It is currently being used as a model for the Air Force in their ICAM program, and the chart that was presented earlier in these hearings on the IGIS standard was in fact a result of this core group that was originated by the IPAD activity. I would like to suggest that you examine the process that we went through in forming the IPAD program as one way to help the transfer of technology. Technology transfer is an issue that we face in most of the work that we do in advanced aerospace technology and it is certainly a core issue for industrial automation.

Mr. **Gore**. OK. Other responses? Dr. Lyons?

Dr. **Lyons**. I would just like to observe that the five-point program that you presented shows the magnitude of the commitment from across the ocean, and that we do need an appropriate matching response but I am not clear that it would be in this form at all.

Mr. **Gore**. Yes.

Dr. **Lyons**. Also I would just like to perhaps end my comments with an upbeat note. That is that ultimately, as the gentleman to my right said, this is going to be a software competition in flexible manufacturing and only secondarily a hardware competition. One thing we do in the United States better than anyone else in the world is to write clever software, so I am optimistic that if people are suitably encouraged that we can still prevail in the marketplace.

Mr. **Gore**. Dr. Gevarter?

Dr. **Gevarter**. In following these same comments about ultimately software being perhaps the most important ingredient in robotics and automation, Japan apparently is undertaking something in the order of a $450 million, 10-year program, what they call the fifth generation computer. This whole program is centered around computations based upon artificial intelligence techniques, natural language understanding, image understanding, automatic problem-solving, the generic technology necessary for automation.

In some ways it is a little bit ironic that just as we are beginning to talk about catching up in the hardware aspects, which is the robotics as we know it today, they are actually predicting a decrease in their robotics effort in the future, in the rate of growth, and moving on to what they call an information society in which their value will come from working on information rather than working on manufacturing.

Therefore, I think software is a very important ingredient. They realized they are behind in software. They are buying some software firms in the United States. They are trying to make agreements with the European nations on coming up with the software and artificial intelligence that they need, and I think this is something very much to be considered because the Japanese fully recognize this and they have come up with an ordered program after a 2-year study involving something like 150 people, to overcome this problem. Therefore, I do not think we can sit easy on the software technology, for the future relationship to the Japanese and to the world as well.

Mr. **Gore**. Dr. Martin?

Dr. **Martin**. Well, I do not think those technologies are mutually exclusive. They go hand-in-hand.

However, looking at the near-term solution, and I think everybody here is probably in agreement that something needs to be done and there ought to be some sort of coordinated plan, the question is what form that might take and where the responsibility for coordination should reside.

Within DOD we have the Manufacturing Technology Advisory Group, which is a triservice group that coordinates the manufacturing technology program amongst the services. We have input from six industry organizations, and perhaps some input from them might give some insight into areas in which we might make some immediate gains in expediting the introduction of greater levels of automation in our industry, what incentives we might provide.

Mr. **Gore**. Wouldn't there be some problems with DOD being the lead agency in this effort?

Dr. **Martin**. Well, not in the instance that what we are addressing are, one, DOD problems, and each of these are sanctioned industry organizations. They are sanctioned lobbying groups so they are in a position to advise.

Now, you know, we have been doing this for our own needs. That something similar might be done to satisfy our commercial sector is worthy of investigation.

Mr. **Gore**. Yes. Well, my own tentative conclusion is that the Department of Commerce ought to have an expanded role in this area but again, that is something that is going to have to be hashed over.

Let me recognize the ranking minority member, Mr. Walker.

Mr. **Walker**. Thank you, Mr. Chairman.

A couple of months ago I was at an informal briefing done by some scientists from one of the universities in Pennsylvania that has been doing some computer work— I think it was Carnegie Tech—and at that point they were talking about the possibilities of the United States leapfrogging in robotics. I may have my generations wrong here—you can correct me if I am wrong—but they were talking about the fact that most of the robotics in use in this country for industrial purposes are first generation, that the Japanese had certainly gone to second generation, and that they are working on third and fourth generation and they thought that there was a potential for leapfrogging the Japanese technology and moving directly in this country from first generation applications to third and fourth generation applications. I am wondering what the opinion of this group might be, of the potentials for that, and if indeed it can be done, what incentives are going to be necessary to insure that it does happen?

Dr. **Sanderson**. Mr. Walker, I would comment briefly on that. I think in the high-technology end, the third and fourth generation, we certainly have a very strong base in terms of the fundamental research that we are carrying out in artificial intelligence, sensors, distributed control systems, etc., so the potential really does exist. I see some fairly serious obstacles at the same time.

One of the obstacles was one that was mentioned just before you came in. I returned yesterday from a meeting of the American Society for Engineering Education, and one of the reports there is that the engineering education problem, the faculty shortage, the quality of teaching which has been discussed many times before the Congress, is in fact getting worse. The number of vacant faculty positions is now in excess of 10 percent in engineering departments around the country, and the quality of engineering education as measured by a fairly objective accreditation board, indicates that in over 70 percent of the institutions the quality of education of engineers and computer scientists is in fact declining in this country.

Both of those are, in my mind, very poor harbingers of our ability to leapfrog the Japanese.

Mr. **Walker**. Let me break in there for a moment. Is this figure correct, do you know? Someone gave me a figure the other day that for every thousand lawyers that the Japanese train, they train 10,000 engineers, whereas it is the exact reverse in this country, that we train 10,000 lawyers for every 1,000 engineers. Is that a correct figure?

Mr. **Sanderson**. I cannot give the exact numbers but I do know that is the right ballpark.

Mr. **Gore**. If my colleague will yield, the figures that I have heard are that they are training 4 to 1, four times as many engineers per capita, and we are training 20 times as many lawyers per capita.

Mr. **Walker**. I thank the chairman.

Dr. **Sanderson**. That certainly is a problem. There is, in the forefront research departments like Carnegie-Mellon and some of the other institutions, discussed an ability to leapfrog and go to the next generation of robotics and automation. One of the problems we will encounter is the lack of experience with the current generation, the second and third generation, because a great deal of the difficulty is in the overall system design, the different designs of the manufacturing system needed to effectively use the robot.

I think, on the positive side again, we are seeing a great marrying of the capabilities of software and hardware. We are producing some very good research results in developing specialized chips for special-purpose computing and robot control, for example, parallel array processors which greatly speed up the responsiveness of the robot. A lot of the technology is in fact being developed and has the potential for developing over the next several years. But there still are some major obstacles that I see in the United States being the country that actually leapfrogs into the next generation.

Mr. **Walker**. That is all the questions that I have.

Mr. **Gore**. Well, would you all be willing to answer additional questions in writing for the record? We do not anticipate a great number of them. Is that all OK with everybody?

I hope that we can in pursuing this issue stimulate the process of goal alinement in this area. I think that if we do not have a much more coordinated, accelerated effort, we are really going to lose out.

Dr. Martin, maybe if we get some more money in the Commerce program and get some sophisticated robots, maybe you all can draft them when you need them in the future. [Laughter.]

Mr. **Gore**. Let me thank all of you for coming here today. We could ask questions usefully and productively for a much longer period of time but we anticipate several more votes on the floor. One is there now. We will submit additional questions and the subcommittee's inquiry into this area will be proceeding.

Thank you very much for an excellent testimony.

[Whereupon, at 12:15 p.m., the subcommittee recessed, to reconvene at the call of the Chair.]

APPENDIX

Followup Questions and Answers

DON FUQUA, FLA., CHAIRMAN
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October 13, 1982

Dr. Frederic Weingarten, Program Manager
Communications & Information Technologies
Office of Technology Assessment
Congress of the United States
Washington, D.C. 20510

Dear Dr. Weingarten:

I want to take this opportunity to express my appreciation for your excellent testimony at our recent hearings on robotics technology.

As you may recall, at the hearing I mentioned that additional questions would be submitted to the witnesses in writing. To ensure that the record is complete, I would appreciate your submitting answers to the enclosed questions at your earliest convenience.

If you have any questions, please contact Ray Brill at 225-2891 or Bob Nicholas, Chief Counsel/Staff Director of the Subcommittee at 226-3636.

Thank you again for your assistance in this matter.

Sincerely,

Albert Gore, Jr.

Albert Gore, Jr.
Chairman
Subcommittee on
Investigations and Oversight

AJ:Bbe
Enclosure

1. In your written testimony, you state that we need to know more about the interrelationship between hardware and software systems development, facility layout, product design, and, in particular, the integration of human beings with equipment to gain the fullest improvements in productivity. With respect to integration of human beings with equipment, does this refer only to improved management? If not, please amplify on your statement. I would also appreciate your comments on the efforts of the Japanese in this area.

2. You mentioned that current or anticipated shortage of research manpower presents a crisis situation. Please describe the severity of the shortage and what your recommendations would be to alleviate the situation.

3. Please describe the steps you believe should be taken to ensure a technically literate workforce. How do the present U. S. efforts compare with the Japanese efforts in this regard?

4. How would you describe current federal agency coordination of R&D efforts? Please include in your comments known areas of duplication, recommendations for improvement of the interaction of flow of information, and an evaluation of the current National Science Foundation coordinating mechanism.

5. Do you feel that R&D policy should attempt to stimulate new, emerging industries or assist more mature industries, or both, and why?

6. How do you design R&D programs which take into account the applicability of different technologies to different industries?

7. On page 13 of your written testimony, you enumerated research topics which should be pursued to improve manufacturing technology. These three area include machine control and dynamic systems, tribology and interactive computer graphics. Please describe the research currently being conducted in these areas and compare them with those being conducted by the Japanese.

8. The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

b. I would appreciate your specific comments on how a national plan could assist in the development of:

   (1) software needs

   (2) automated manufacturing systems

   (3) quality assurance

   (4) technology transfer

   (5) data bank of evaluated and demonstrated information

   (6) technical literacy of general population

   (7) sufficient scientific manpower

   (8) incentives for the use of robots and/or automation technologies

c. Should industry set the research priorities?

d. Should government have a coordinative role rather than a centralized management function? and

e. What funding levels would be appropriate and for what period of time?

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Congress of the United States
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JOHN H. GIBBONS
DIRECTOR

NOV 25 1982

The Honorable Albert Gore, Jr.
Chairman
Subcommittee on Investigations
  and Oversight
Committee on Science and Technology
U.S. House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed are my responses to the supplemental questions in your letter of October 13.

As mentioned in my testimony, the OTA program that I direct is engaged in a number of related activities. We have just completed a study, Information Technology in American Education, that explores the changing demands of an "information society" on the U.S. education system. We are currently part way through a study of computerized automation and manufacturing. Finally, we have forwarded to the Technology Assessment Board a proposal for an assessment of research and development in communication and information technology. The House Committee on Science and Technology was one of the requestors of that study. We hope that the results of these studies will provide more definitive answers to some of the difficult questions you raised.

Thank you for the opportunity to participate in this interesting set of hearings. If we can provide any further information or assistance, please let us know.

Sincerely yours,

Fred W. Weingarten
Program Manager
Communication and
Information
  Technologies Program

Enclosure:

1. The study of integrating of human beings with the machinery of automation certainly includes management techniques and the overall organization of production in a factory. However, it also includes designing automated systems with the needs and skills of the work force in mind. Automated machines, themselves, need to be designed to be easily monitored, controlled, programmed, and repaired by humans. At a higher, but equally important level of aggregation, the overall production line design shapes the nature of work in a factory. Flexible manufacturing may allow much more leeway than previous "hard" automation to design a production process that incorporates the skills and needs of the labor force. Many reports indicate that Japanese automation projects take into account during design and implementation the overall management and organization of work in the factory.

2. Reports of critical shortages of technical manpower are examined in the OTA report "Informational Technology and Its Impact on American Education." In addition, the National Science Foundation is currently examining this question and probably has some good data. The shortage is at two levels--(1) design technicians and programmers who can implement new automation systems and (2) research level scientists and engineers who can advance the state of the art. If these reported shortages do exist, they would serve as a significant drag on any attempt to rapidly advance the use of programmable automation in U.S. industry.

3. The OTA education report, cited above, discusses in general the need for greater technical literacy in the United States. The automation study will examine the implications of programmable automation for entry level skills. We did not specifically examine Japanese efforts; however, NSF studies indicate a much higher level of technical literacy in the Japanese workforce.

4. The automation and research and development projects will be looking at Federal R&D programs in a variety of computer and communication technologies, including robotics and automation. We do not have enough information as yet to draw conclusions.

5. At the generic, or basic research level, it is difficult to determine whether any particular type of industry is favored. At the applied or developmental level, certain types of projects may favor one type of industrial process over another--say, small scale batch assembly over large scale process. However, programmable automation is, itself, a new and emerging industry. To that extent, any R&D in this area helps the new, even if its application is to the old.

6. The automation and R&D studies will explore in detail alternative roles for the Federal government to stimulate or support R&D in communication and information technologies.

7. The automation assessment will have a major portion devoted to such an analysis. Data gathering is just under way.

8. At this early stage of the automation study, OTA is not prepared to comment on alternative Federal policies to promote the development and use of automation technology. However, this topic is one of the principal focii of OTA"s ongoing assessment "Automation and the Workplace."

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October 13, 1982

Lee B. Holcomb, Manager
Computer Science and Electronics
Office of Aeronautics & Space Technology
Nat'l Aeronautics & Space Administration
Washington, D.C. 20546

Dear Mr. Holcomb:

I want to take this opportunity to express my appreciation for your excellent testimony at our recent hearings on robotics technology.

As you may recall, at the hearing I mentioned that additional questions would be submitted to the witnesses in writing. To ensure that the record is complete, I would appreciate your submitting answers to the enclosed questions at your earliest convenience.

If you have any questions, please contact Ray Brill at 225-2891 or Bob Nicholas, Chief Counsel/Staff Director of the Subcommittee at 226-3636.

Thank you again for your assistance in this matter.

Sincerely,

Albert Gore, Jr.

Albert Gore, Jr.
Chairman
Subcommittee on
Investigations and Oversight

AJ:Bbe
Enclosure

1. You stated that in 1980 you held a 10-week workshop to study the feasibility of using robotics and automation in future space missions. Your major emphasis seems to be teleoperator systems and you envision the day the teleoperator would be an intelligent robot:

   a. When do you expect that to occur?

   b. Does NASA consider the development of robotics technology a high priority?

   c. If so, do you expect funding levels to increase above $3 million?

2. You mention four areas which deserve attention:

   1. sensor systems
   2. artificial intelligence techniques for planning problem-solving and decision-making
   3. adaptive control for high-speed, structurally flexible effectors
   4. robot programming languages

      a. What is NASA doing presently in each area?

      b. What are your long-term plans?

3. When do you expect to be able to integrate real-time vision with force, position and touch sensors?

4. You mentioned that additional technological development is required in advance programming languages:

   a. Describe your progress so far.

   b. What collaboration do you have with leading universities that are doing extensive research in this area?

5. You mentioned that industry is inclined to support efforts which yield short-term returns and the Federal Government supports longer-term, risky research:

a. How relevant is your long-term research in teleoperators and sensors, for example, to industrial needs?

b. How much of your research can be spun-off for industrial use in a practical sense without considerable investment on their part?

6. The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

   a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

   b. I would appreciate your specific comments on how a national plan could assist in the development of:

      (1) software needs

      (2) automated manufacturing systems

      (3) quality assurance

      (4) technology transfer

      (5) data bank of evaluated and demonstrated information

      (6) technical literacy of general population

      (7) sufficient scientific manpower

      (8) incentives for the use of robots and/or automation technologies

   c. Should industry set the research priorities?

   d. Should government have a coordinative role rather than a centralized management function? and

   e. What funding levels would be appropriate and for what period of time?

RESPONSES TO WRITTEN QUESTIONS SUBMITTED BY CONGRESSMAN GORE DURING THE HEARING ON ROBOTICS TECHNOLOGY BEFORE THE HOUSE SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT ON JUNE 23, 1982, TO MR. HOLCOMB

QUESTION R-1:

You stated that in 1980 you held a 10-week workshop to study the feasibility of using robotics and automation in future space missions. Your major emphasis seems to be teleoperator systems and you envision the day the teleoperator would be an intelligent robot:

a. When do you expect that to occur?

b. Does NASA consider the development of robotics technology a high priority?

c. If so, do you expect funding levels to increase above $3 million?

ANSWER R-1:

a. A first generation free-flying space teleoperator could be operational by the late 1980's. At present there is no approved flight project moving in this direction, although several competing concepts have been defined. Projecting a date of operational readiness for an "intelligent robot" is speculative, at best, on two counts. First - what definition of intelligent should be used? Second - our ability to predict the technological future beyond five years is very poor, and an intelligent robot by any reasonable measure is well over five years away. Suppose we consider a robot to be intelligent that can:

1. move about on unknown terrain effectively,

2. sense its environment using multiple sensing modes and integrate that information into a model of its operational environment,

3. manipulate objects in its environment with dexterity, using sensory information to provide robust control, and

4. plan its activities based on a high level goal statement, execute its plan, monitor its activities, and replan around contingencies.

Conceivable, an intelligent robot of demonstrable capability may be seen, perhaps in as little as ten years. A more reasonable expectation is 15-20 years. A space-qualified intelligent robot will likely not be operational for at least 20 years.

b. The robotics technology program is considered of importance to future NASA programs, and it is attracting increased attention within the Agency. Within the NASA Space Technology program, robotics technology represents 2.5 percent of the budget. This is consistent with the NASA policy of support to some 20 to 30 critical space technologies.

c. Technology funding levels are expected to exceed $3 million in FY 1984. A 50 percent growth represents an upper bound on this planned program growth. This growth is dependent on the Agency budget posture for FY 1984.

QUESTION R-2:

You mention four areas which deserve attention:

1. sensor systems
2. artificial intelligence techniques for planning, problem-solving, and decision-making
3. adaptive control for high-speed, structurally flexible effectors
4. robot programming languages

a. What is NASA doing presently in each area?

b. What are your long-term plans?

ANSWER R-2:

1. Sensor systems - NASA is conducting research on robot vision systems for real-time control at the Jet Propulsion Laboratory (JPL). Langley Research Center (LaRC) is developing a Teleoperator and Robotics System Simulator (TRSS) to evaluate alternative control, display, and sensing modes for space teleoperator and robotic systems.

JPL is progressing toward a 1986 demonstration of a real-time control-oriented robot vision system. LaRC is developing the laboratory capability to integrate sensing component concepts and technologies into hypothetical systems and to evaluate their performance in a system context through trade-off studies.

2. Artificial intelligence techniques -JPL has developed a prototype planner called DEVISER which has demonstrated capabilities for planning and scheduling spacecraft command sequences for deep-space missions such as Voyager and Galileo. A replacement of its "knowledge base" tailored to the robot planning problem would yield a rudimentary robot planner. In addition, NASA has identified expert systems as a key technology for automated problem-solving and decision-making. We are presently building institutional capability in this important area.

DEVISER is being extended and modified to form a new program called FAITH which will perform fault diagnosis and interpretation. In the long term, the planning and fault diagnosis capabilities will be integrated to provide the type of robust planning and operations monitoring required for robotic systems operating in loosely structured environments. Expert systems technology will be selectively employed to perform system monitoring and operational control tasks.

3. Adaptive control - NASA is supporting fundamental research at Stanford University investigating adaptive control of high-speed, structurally flexible manipulators. Current activities are focusing on a one-link, one degree-of-freedom arm, for which real-time control algorithms for a pick and place function were demonstrated in 1982.

Future work at Stanford will address multiple-link arms with one degree-of-freedom at each joint, and subsequently multiple degrees of freedom at each joint. Robust control of a robot manipulator requires an ability to adapt to changing mass properties, as the manipulator picks up objects and subsequently sets them down. Estimation algorithms are an important part of adaptive control and will also be addressed by Stanford.

4. Robot programming languages - We are beginning an effort in FY 1983 to develop a sensor-based robotic/teleoperator control language.

In the long term, we hope to have a language capable of describing in a simple, user-friendly manner the generic characteristic of tasks common to space activities. It must allow generic naming and coding conventions (representations), and it must incorporate linguistic means (a language) for describing sensor motor sequences at a level high enough that it is convenient for human operators. In addition, methods for instantiating and executing the sensor referenced models must be developed.

QUESTION R-3:

When do you expect to be able to integrate real-time vision with force, position and touch sensors?

ANSWER R-3:

NASA believes the integration of real-time vision with force, position and touch sensors will be feasible and demonstrable in the period of 1988-1990.

QUESTION R-4:

You mentioned that additional technological development is required in advanced programming languages:

a. Describe your progress so far.

b. What collaboration do you have with leading universities that are doing extensive research in this area?

ANSWER R-4:

a. NASA has worked with the DOD evaluating the potential role of the Ada language in NASA. Under a grant with the University of Illinois, Path Pascal has been developed. This language is particularly useful as an implementation language for multi-processor operating systems. Of more direct importance to robotics, the JPL Autonomous Robot Systems (JARS) language, a modular Pascal-based robot language, has been developed which will provide the foundation for subsequent robot control language development.

b. We have had close collaboration with the University of Illinois on Path Pascal and with Stanford University on robot control languages. In addition, we participate in the University of Rhode Island's Robotics Consortium and collaborate with the Massachusetts Institute of Technology on teleoperation systems and concepts.

QUESTION R-5:

You mentioned that industry is inclined to support efforts which yield short-term returns and the Federal Government supports longer-term, risky research:

a. How relevant is your long-term research in teleoperators and sensors, for example, to industrial needs?

b. How much of your research can be spun-off for industrial use in a practical sense without considerable investment on their part?

ANSWER R-5:

a. We haven't assessed long-term industrial needs in teleoperators and sensors. Advances in real-time computer vision are needed for us to effectively perform manipulative tasks remotely (e.g., in space). We are pushing this area and observe that the generic requirements we are addressing, including real-time response and object recognition and tracking over a cluttered background, are shared at some level in the industrial sector. Currently, industrial robots are limited to application in highly structured environments. Parts to be assembled, for example, must typically be in precise locations and orientations or on high contrast planar surfaces. Robust vision is an exceedingly complex sensory mode, which is also exceedingly valuable. We are addressing what we consider to be the important aspects of the problem for space applications and believe there exists substantial relevance to industrial needs. Similarly, our work in teleoperation is generic but focussed on space-related tasks. There is some inherent commonality between terrestrial teleoperation applications and space, particularly in undersea applications.

There are also unique problems to the space environment, not shared in the commercial sector, to which we must attend. Perhaps the most significant of these is the zero gravity environment, enabling the movement of immense, awkward objects with seemingly flimsy devices. Harsh lighting and lack of atmosphere are also unique attributes of the environment in which our systems must function. With our limited resources, we try to focus on technological problems and issues which will not be addressed by other organizations, and, hence, tend to dwell on issues unique to the space environment.

b. The work in robot vision is being spun off very practically. The NASA Technology Utilization Office, in conjunction with two industrial suppliers, is developing a program to implement NASA-developed vision algorithms in Very Large Scale Integration (VLSI) devices for incorporation in commercial computer vision systems. Our research in planning and problem-solving is also generic enough and focussed sufficiently that technology transfer is not impeded. Our work in system-level simulation may not be spun off quite so easily to the nonaerospace sector, however, since it focuses more specifically on space applications. The simulation techniques could be adapted, but with moderate investment.

QUESTION R-6:

The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

b. I would appreciate your specific comments on how a national plan could assist in the development of:

(1) software needs

(2) automated manufacturing systems

(3) quality assurance

(4) technology transfer

(5) data bank of evaluated and demonstrated information

(6) technical literacy of general population

(7) sufficient scientific manpower

(8) incentives for the use of robots and/or automation technologies

c. Should industry set the research priorities?

d. Should Government have a coordinative role rather than a centralized management function? and

e. What funding levels would be appropriate and for what period of time?

ANSWER R-6:

NASA has not developed a policy with regard to a national plan in robotics and is not in a position to provide specific responses to elements of this question. NASA endorses appropriate Government sponsored programs to provide a nucleus of continuing support for long-term, high-risk and potentially high-payoff robotics and automation research.

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DAVID S. JEFFERY
MINORITY STAFF DIRECTOR

October 13, 1982

Dr. John W. Lyons, Director
Nat'l Engineering Laboratory
Nat'l Bureau of Standards
Washington, D.C. 20234

Dear Dr. Lyons:

I want to take this opportunity to express my appreciation for your excellent testimony at our recent hearings on robotics technology.

As you may recall, at the hearing I mentioned that additional questions would be submitted to the witnesses in writing. To ensure that the record is complete, I would appreciate your submitting answers to the enclosed questions at your earliest convenience.

If you have any questions, please contact Ray Brill at 225-2891 or Bob Nicholas, Chief Counsel/Staff Director of the Subcommittee at 226-3636.

Thank you again for your assistance in this matter.

Sincerely,

Albert Gore, Jr.

Albert Gore, Jr.
Chairman
Subcommittee on
Investigations and Oversight

AJ:Bbe
Enclosure

1. You discuss the Automated Manufacturing Research Facility and how it will assist NBS in establishing standards for the many interfaces between the components of computer and manufacturing systems.

    a. How does the inability to couple directly between components made by different manufacturers affect productivity?

    b. Won't you AMRF approximate a flexible manufacturing system?

    c. How would you assess our FMS capabilities vis-a-vis Japan?

2. In what ways can government be an effective facilitator and catalyst for establishing standards without interfering?

3. Have any health and safety standards been set?

4. One of the big problems in the United States is not the generation of technology, but in taking it from the universities to users in real time. Usually, a university report doesn't show up in the NTIS registry until 6-12 months later. The Japanese take a much more aggressive approach.

    a. What can NBS or other federal agencies do to facilitate this transfer of information?

    b. What can NBS or other federal agencies do to speed the translation of important technological documents?

5. The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

    a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

    b. I would appreciate your specific comments on how a national plan could assist in the development of:

        (1) software needs

        (2) automated manufacturing systems

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(4) technology transfer

(5) data bank of evaluated and demonstrated information

(6) technical literacy of general population

(7) sufficient scientific manpower

(8) incentives for the use of robots and/or automation technologies

c. Should industry set the research priorities?

d. Should government have a coordinative role rather than a centralized management function? and

e. What funding levels would be appropriate and for what period of time?

John W. Lyons
Director, National Engineering Laboratory
National Bureau of Standards

Response to Additional Questions from
Albert Gore, Jr.
Chairman, Subcommittee on Investigations and Oversight
Committee on Science and Technology

Question 1: You discuss the Automated Manufacturing Research Facility and how it will assist NBS in establishing standards for the many interfaces between the components of computer and manufacturing systems.

a. How does the inability to couple directly between components made by different manufacturers affect productivity?

Answer: The goal of the United States' collective efforts in automated manufacturing is to reap the benefits of improved productivity. The General Accounting Office has estimated up to 300% increases in productivity could be realized through automation. The NBS program addresses technical problems appropriate to our mission. We believe the technical problems described in my testimony before the Subcommittee represent significant barriers to the adoption of automation and their solution will greatly enhance the rate of diffusion of the technology. (Obviously there are many non-technical barriers; we do not address these at NBS.) I cannot estimate the relative significance of the various technical problems in terms of the 300% target. All I can say is I am convinced they are major items on anybody's list.

The argument for modularity or coupling components together goes as follows. First, if the systems available for purchase are too large, inflexible in design, and limited in scope, few would buy and the positive impact on national productivity would be slight. By making the system modular and, through software interfaces such as IGES, making the components interchangeable, the buyer would be able to purchase a system to match his needs and financial capabilities. He would then be able to build up his Flexible Manufacturing System (FMS) at a rate suited to his situation and using modules that very closely meet his special needs. We believe this condition would accelerate the purchases of FMS components and thereby reap the productivity benefits more quickly. This would be the national impact.

Second, at the level of the individual firm, there would be additional benefits in improved productivity of capital and operating cash. In the absence of non-proprietary interfaces, the buyer would have to provide his own interface software. For a large or small firm this would be expensive. A large firm might do the work itself. In that case it would be a drain on engineering resources. Smaller firms would have to lay out cash for customized software.

The non-proprietary software interfaces would cut out this problem and the associated extra costs.

For the smallest firms (and in the discrete parts business some 87% employ less than 50 persons) this could make the difference between automating and remaining behind. For those who do automate the savings in software investments would appear as an improvement in the productivity of capital.

In summary, non-proprietary interfaces which permit easy coupling of modules in the factories of the future are necessary, on the national level, to capture major increases in productivity through their effect on the rate of diffusion of new automation technology, at the level of the individual firm, to make possible higher rates of return on new investments.

b. Won't your AMRF approximate a flexible manufacturing system?

Answer: Yes, the NBS AMRF will approximate a flexible manufacturing system (FMS). However, instead of choosing the components for their compatibility, we are selecting components from a number of manufacturers to serve as a research test bed for the development of software interface standards. The AMRF as its name implies is a research facility. It is designed to "emulate" certain portions of any flexible manufacturing system. Where "emulate" means model at full scale in real time, and where the portions include the control system and those systems which provide the quality assurance through traceability to national standards. Hence, the AMRF will be like no flexible manufacturing system that will ever be built, but in important aspects we shall be able to make it behave like any flexible manufacturing system.

c. How would you assess our FMS capabilities vis-a-vis Japan?

Answer: The Japanese industry has adopted FMS to an extent which far exceeds the U.S. They have perhaps five times the number of such systems that we do, in place and operating. They displayed, at the machine tool show this year in Chicago, perhaps the most sophisticated system available on the open market. However, the Japanese are not ahead of the U.S. as far as underlying technology goes. The manufacturing research conducted at American universities, at NBS, and elsewhere appears to be in advance of that in Japan. The Japanese appear to be behind the U.S. in control, computer, and software research as it relates to FMS. It is our belief that these areas will dominate in the factory of the future, and our advantage in research represents the best hope of the U.S. to regain its position in manufacturing.

Question 2: In what ways can government be an effective facilitator and catalyst for establishing standards without interfering?

Answer: I do not feel qualified to speak for the entire Federal Government, since particular agency responsibilities and missions, such as defense, may necessitate different roles. However, I can describe how NBS facilitates the establishment of standards without interfering. NBS does not issue automation interface or measurement standards. Instead, we work with other agencies and the various voluntary standards organizations concerned with developing standards. NBS provides technical knowledge and leadership when needed. NBS has a long history of playing the neutral third party role in such standards organizations and facilitating the establishment of standards without interfering. I believe an excellent example of this is illustrated by our work in developing the Initial Graphics Exchange Specifications (IGES) which I discussed in my testimony.

Question 3: Have any health and safety standards been set?

Answer: Not in the U.S. At a recent meeting at NBS, attended by the representatives of all the major standards bodies in this field, the Robot Institute of America and Underwriters Laboratory reported initial efforts to organize standards writing committees to work on safety standards.

Question 4: One of the big problems in the United States is not the generation of technology, but in taking it from the universities to users in real time. Usually, a university report doesn't show up in the NTIS registry until 6-12 months later. The Japanese take a much more aggressive approach.

a. What can NBS or other federal agencies do to facilitate this transfer of information?

Answer: NBS has many mechanisms to facilitate the transfer of our research findings to potential users. The business of the NBS is the transfer of our research findings, measurements, standards, data, and test methods to U.S. industry, public, all levels of government, and academia. The Bureau has a wide range of technology transfer activities which by design are an inseparable and integral part of the NBS programs. The NBS has also established in response to the Stevenson-Wydler Innovation Act of 1980 (Pub.L. 96-480) an Office of Research and Technology Applications (ORTA) that has agency-level responsibility for technology transfer to private industry and to state and local governments. ORTA monitors and provides a focal point for many NBS technology transfer activities. Some of the principal means are:

- Research Associates and Guest Workers: Under these programs professional staff from the private sector, universities, and other government agencies, work at NBS with our professional staff. This program not only provides an infusion of skills and knowledge that contribute to the research effort but also provides a very effective means for transferring the research results when the worker returns home.

- Workshops and Measurement Courses: Often after NBS has developed a new measurement technique, we conduct a "hands-on" workshop to train interested parties in how to use the new technique. Examples are the linewidth workshops NBS conducted for the semiconductor industry. We gave the participants of these workshops the theory of the measurement and hands-on experience in making the measurement. Interactions between the users and our staff provide constructive feedback on the spot to correct any misunderstandings.

- Publications: Besides publishing our results in scholarly scientific or engineering journals, we also have NBS publications in which we can publish our work in greater detail which facilitates the applications of our results. These publications are widely distributed and available to the users.

- Standards Committees: NBS has hundreds of its staff serving on standards committees. Often they are serving at the specific request of the committee. Our staff communicate our most recent technical results directly to many of the interested parties at various committee meetings.

I have been advised by DoC Counsel that, in the broader context, recently enacted Patent legislation (Pub. L. No. 96-517) has addressed this issue. By giving universities the ownership of patents to technology developed under government contracts and grants, they will have increased incentives to license or otherwise transfer the technology to the private sector. Preliminary information indicates that universities are now licensing nearly one half of their patent inventory.

b. What can NBS or other federal agencies do to speed the translation of important technological documents?

Answer: I have no suggestions on this matter since we do not have a problem in obtaining timely translations of available technical documents required for our research.

Question 5: The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

b. I would appreciate your specific comments on how a national plan could assist in the development of:

(1) software needs
(2) automated manufacturing systems
(3) quality assurance
(4) technology transfer
(5) data bank of evaluated and demonstrated information
(6) technical literacy of general population
(7) sufficient scientific manpower
(8) incentives for the use of robots and/or automation technologies

c. Should industry set the research priorities?
d. Should government have a coordinative role rather than a centralized management function? and
e. What funding levels would be appropriate and for what period of time?

Answer: In general, the Administration believes that it is the private sector's responsibility to develop and commercialize new technologies. The primary role of the Federal government should be limited to providing for underlying basic research, where appropriate, and creating an economic climate with sufficient incentives to encourage appropriate private sector investment decisions.

While I am not in position to propose a National plan to promote robotics and automation technologies, I am aware of the issues, the technology, and the concerns of the many parties involved. It is quite evident from the testimony presented at these hearings as well as the extensive discussions that have taken place in all parts of government and the private sector that these technologies can have dramatic effects on the Nation's productivity and economy. I think we all recognize that while there are many technological issues, the approach the United States takes should also deal with the social and economic impacts.

In my work as a member of NSF's Advisory Committee on Engineering I have become aware of the deep concern over how we shall meet the education and training requirements that are associated with the manufacturing automation efforts that this Nation must undertake. Likewise, in serving on the Advisory Council of the University of Maryland School of Engineering and in my interactions with other universities I have seen the need for revising and upgrading our educational programs to improve the education of our scientists and engineers to cope with emerging technologies.

Through NBS' continuing dialogue with industry, we identify research problems and technological barriers that need to be addressed. I conclude that in any national effort all the parties must be involved. Government has a role to play in such an effort, but it should be a cooperative role and one of providing the necessary nonproprietary technology which the private sector cannot undertake (and such as I described in my testimony on NBS' program before the Subcommittee) rather than a role of Government assuming a centralized management function or of attempting to conduct the entire effort itself.

Appropriate funding levels for such an effort must consider the contributions being made by all parties, not only Government. In addition, economic incentives would have to be considered to encourage the use of robotics and automation technologies. As such it would be presumptuous of me to estimate a funding level for such a program. Such an estimate would be more appropriate if developed jointly by all parties concerned in the Administration, Congress, and the public and private sectors. For comparison purposes it would be useful to assemble estimates of funding in Japan and West Germany, government and private. There are some numbers available but I think a fresh assessment of the best information would be useful to the Subcommittee. I believe that there is an important role for industry, universities, and the Government to play in this area.

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MINORITY STAFF DIRECTOR

October 13,1982

Dr. James S. Albus, Acting Chief
Industrial Systems Division
National Bureau of Standards
Washington, D.C. 20234

Dear Dr. Albus:

I want to take this opportunity to express my appreciation for your excellent testimony at our recent hearings on robotics technology.

As you may recall, at the hearing I mentioned that additional questions would be submitted to the witnesses in writing. To ensure that the record is complete, I would appreciate your submitting answers to the enclosed questions at your earliest convenience.

If you have any questions, please contact Ray Brill at 225-2891 or Bob Nicholas, Chief Counsel/Staff Director of the Subcommittee at 226-3636.

Thank you again for your assistance in this matter.

Sincerely,

Albert Gore, Jr.

Albert Gore, Jr.
Chairman
Subcommittee on
Investigations and Oversight

AJ:Bbe
Enclosure

1. You have been quoted as saying:

   "The human race is now poised on the brink of a new industrial revolution which will equal, if not exceed, the first Industrial Revolution and its impact on mankind. The first Industrial Revolution was based on the substitution of mechanical energy for muscle power. The next Industrial Revolution will be based on the substitution of electronic computers for the human brain in the control of machines and industrial processes."

   a. What are the future implications of this robotics technology for the manufacturing industry?

   b. What types of development do you envision likely to occur during this century?

   c. What types of development do you foresee for the next century?

2. How would you assess the technical literacy of our workers? In this connection, what steps do you feel need to be taken to retrain this workforce?

3. Finally, what do you feel we can borrow from foreign models in robotics research?

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

November 9, 1982

Honorable Albert Gore, Jr.
Chairman, Subcommittee on
Investigations and Oversight
Committee on Science and Technology
House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman:

I am flattered by your interest in my opinions on the social and economic implications of robotic technology. I have spent considerable time over the past 15 years thinking about this subject. As you may already know, the quote you attribute to me was taken from my book on the Economics of the Robot Revolution published in 1976.

In answering your questions, however, I must declare that my opinions on the subject of sociology and economics are those of a concerned layman only. My position as Acting Chief, Industrial Systems Division at the National Bureau of Standards is a technical and managerial one in the field of computer science and robotics applied to manufacturing engineering. I am not in a position to speak for the National Bureau of Standards or the Department of Commerce on social, political, or economic matters.

Nevertheless, I am happy to venture my personal opinion which is being submitted by separate letter, attached.

Sincerely,

James S. Albus, Ph.D.
Acting Division Chief
Industrial Systems Division

Enclosure

November 9, 1982

Honorable Albert Gore, Jr.
Chairman, Subcommittee on
Investigations and Oversight
Committee on Science and Technology
House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman:

Robotics technology (broadly interpreted to include computers, numerically controlled machine tools, automatic materials inventory and transport systems, automatic production planning, and computer aided design and process planning systems integrated into the automatic factory) will completely revolutionize the manufacturing process. I believe that the factory of 2082 will be as different from the factory of 1982 as the factory of 1982 was different from that of 1782. This implies that those industries that do not exploit this new technology will simply die, and those countries that do not promote this technology in their domestic industries will rapidly join the ranks of the technologically backward nations. They will become economically impoverished, militarily weak, and politically impotent.

I believe that robotics technology has enormous potential for improving productivity, creating material prosperity, and promoting real economic growth. Automatic factories may cost no more than conventional factories even in the first generation, and they have a powerful capability for self reproduction -- that is, automatic factories will be able to make most of the components for automatic factories. The implications of this are that each generation of automatic factories can be less expensive and more sophisticated than its predecessor. Since automatic factories will have very few labor costs, total manufacturing costs should spiral downward at an exponential rate.

The effects of an analogous self reproductive process in a high technology industry can be seen in the computer industry where there has been a 20% per year decrease in the cost of computing for almost three decades. This amounts to a factor of ten decrease per decade, or about a factor of one thousand since 1950. In large measure this spectacular productivity performance has been due to the regenerative effect of using computers to design, manufacture, test, and program computers.

If anything like the cost/performance ratio of the computer industry occurs in the manufacturing industries, it will have a profound impact on every type of manufactured product, every type of construction, and many types of transportation, communication, health care, food, fuel, and entertainment products. Thus, the potential future implications of robotic technology are enormous and they may profoundly alter the course of human civilization.

The types of development that I envision likely to occur during this century are the following:

During the decade of the 1980's I expect robot arc welding to become the dominant application area. This will effect the cost and quality of trucks, construction machinery, ships, and a wide variety of structural components. During the 1990's, robots integrated into automatic manufacturing systems will become common. Robot assembly will gradually become an important factor, and toward the end of the century, robots may begin to play an important role in construction industries, starting with ship building, and spreading to commercial and eventually residential construction. Also during the 1990's robots may begin to appear in military applications such as ammunition resupply, reconnaissance, clearing of mine fields, and eventually in operating weapons systems.

Early in the next century the totally automatic factory will begin to have a significant economic impact, and home robots will become practical on a large scale. Throughout the next century, robots and automatic factories will grow in importance to become a major, and perhaps dominant factor in the economic health of nations. Robots will mine the ocean floor and farm the surface of the seas for food as well as fuel. By the end of the next century, robots may become as common as automobiles and television sets and ever so much more useful in a variety of ways. For example, an industrial robot generates around $30,000 value added per year. Thus, if everyone owned an industrial robot, everyone would have sufficient income from the robot to be financially independent regardless of whether they were employed or not.

Unfortunately, the present workforce is largely unprepared for the new job skills that will be needed in an economy based on robot labor. New curricula need to be developed, and major job retraining mechanisms need to be established. Hopefully, the jobs created by the need to reeducate the workforce, together with those created by the need to rebuild the nation's industrial base to incorporate this new technology, should more than compensate for jobs lost due to robot installation.

As to what we can learn from foreign models in robotics research, I think there are several possibilities. The first is that the establishment of several well-funded centers of research excellence is extremely important. A second is that a well conceived plan which identifies important industrial problems and focuses research in these areas can speed the transfer of technological knowledge into practice. A third is that there is nothing basically wrong with research in the United States. For the most part, it is American robotics research that is being put into practice in foreign countries, and often by persons educated in American universities. This is no cause for complacency, however, because foreign governments (most notably the Japanese and the French) are now in the process of massively funding robotics research of their own on a scale that in some cases far exceeds current U.S. funding. Thus, greater efforts will be required in this country to keep from falling behind in the basic research which is currently our principal strong point.

I hope these answers are responsive to your inquiry. If you have any further questions I would be happy to try to answer them.

Sincerely,

James S. Albus

James S. Albus, Ph.D.
Acting Division Chief
Industrial Systems Division

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MINORITY STAFF DIRECTOR

October 13, 1982

Dr. Edith W. Martin
Deputy Undersecretary of Defense
 for Research & Advanced Technology
U. S. Department of Defense
Washington, D.C. 20301

Dear Dr. Martin:

I want to take this opportunity to express my appreciation for your excellent testimony at our recent hearings on robotics technology.

As you may recall, at the hearing I mentioned that additional questions would be submitted to the witnesses in writing. To ensure that the record is complete, I would appreciate your submitting answers to the enclosed questions at your earliest convenience.

If you have any questions, please contact Ray Brill at 225-2891 or Bob Nicholas, Chief Counsel/Staff Director of the Subcommittee at 226-3636.

Thank you again for your assistance in this matter.

Sincerely,

Albert Gore, Jr.

Albert Gore, Jr.
Chairman
Subcommittee on
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AJ:Bbe
Enclosure

1. How do you feel that DOD/university/industry cooperation can be improved?

2. Does industry have any input into basic research supported by DOD? Please give us some examples.

3. Do you feel more of your Manufacturing Technology Program research results should be transferred to industry, and, if so, what recommendations do you have for improvement?

4. Do you know of any duplication of research among the federal agencies?

5. If there is no formal coordination between DOD and other federal agencies conducting robotics research, do you feel there is a need for such?

6. The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

   a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

   b. I would appreciate your specific comments on how a national plan could assist in the development of:

      (1) software needs

      (2) automated manufacturing systems

      (3) quality assurance

      (4) technology transfer

      (5) data bank of evaluated and demonstrated information

      (6) technical literacy of general population

      (7) sufficient scientific manpower

      (8) incentives for the use of robots and/or automation technologies

   c. Should industry set the research priorities?

   d. Should government have a coordinative role rather than a centralized management function? and

   e. What funding levels would be appropriate and for what period of time?

DoD/University/Industry Cooperation

Question 1: How do you feel that DoD/university/industry cooperation can be improved?
Answer: Development of good cooperation among DoD, industry and universities is an item of high priority within the Department of Defense. Workshops and symposia play an important role by providing a dialogue to develop a better understanding of industry's needs and to identify university research developments ripe for application. In the robotics and manufacturing technology area, most of our major research initiatives involve joint industry-university projects aimed at rapid implementation of new technological results. Moreover, we are encouraging industry, through the independent research and development program, to increase its interactions with and support of universities.

Industry Input to Basic Research

Question 2: Does industry have any input into basic research supported by DoD? Please give us some examples.
Answer: Interactions with industry play an important role in formulating basic research plans. As an example, the Navy and the National Bureau of Standards are sponsoring a conference at which industrial people will discuss their views on manufacturing and equipment maintenance problems. Out of this and a follow-up conference that will delve into the technical issues raised by these problems, two or three prototype projects will be initiated at the Bureau. These projects will receive Navy funding as well as support from DoD university contractors and industrial volunteers. The goal of the program is industry implementation of the results in real, working environments. Of course, joint university-industry research programs of the type between Westinghouse and Carnegie-Mellon University or between IBM and MIT are a particularly effective way for industry to have an input into basic research directions.

Technology Transfer

Question 3: Do you feel more of your Manufacturing Technology Program research results should be transferred to industry, and, if so, what recommendations do you have for improvement?
Answer: We are confident that the approaches we are taking will ensure rapid transfer of results into industry. These include industrial input into the problems that should be addressed, joint university-industry projects, and industrial advisory boards for university centers of excellence. In addition, the preponderance of the Manufacturing Technology Program efforts are accomplished by industry.

Duplication of Research

Question 4: Do you know of any duplication of research among the federal agencies?
Answer: We are not aware of any duplication of research among federal agencies. The government community involved with robotics and robotics technology is still relatively small so that ad hoc person-to-person interactions and participation in robotics activities are sufficient to avoid this problem. The field is currently at an early and dynamic stage. We, therefore, encourage competitive approaches to similar problems. However, this should not be confused with duplication.

Interagency Coordination of Robotics Research

Question 5: If there is no formal coordination between DoD and other federal agencies conducting robotics research, do you feel there is a need for such?
Answer: To date the number of individuals in government involved in technologies specifically identified as being related to robotics has been relatively small and informal coordination has sufficed. This has led to joint ventures such as the one between the Navy and the National Bureau of Standards discussed earlier. As the program grows and the disciplines involved increase in number, we would not be adverse to an interagency coordinating group whose function would be to provide a forum for information exchange.

National Plan

Question 6: The following questions are concerning a national plan to promote robotics and/or automation technologies. Such a plan should address four major areas: research, development, implementation, and education and training.

a. Please describe how each area could best be developed and the role you believe should be played by industry, universities and government.

b. I would appreciate your specific comments on how a national plan could assist in the development of:
   (1) software needs
   (2) automated manufacturing systems
   (3) quality assurance
   (4) technology transfer
   (5) data bank of evaluated and demonstrated information
   (6) technical literacy of general population
   (7) sufficient scientific manpower
   (8) incentives for the use of robots and/or automation technologies

c. Should industry set the research priorities?

d. Should government have a coordinative role rather than a centralized management functions? and

e. What funding levels would be appropriate and for what period of time?

Answer: We are not convinced that a national plan, either to advance the state-of-the-art in robotics and robotics technology or to encourage use of this technology in the industrial base, would facilitate meaningful progress in the area. In the case of technology development, this is particularly true if by a national plan is implied top down, centrally managed, interdepartmental allocation of resources. The missions, functions, and scope of the various government agencies and departments involved are so diverse that central planning and/or control, in our opinion, is neither realistic nor viable. In the case of the use of robotics, we believe the government should rely on the incentives of the free enterprise system to encourage the use of robots where there is economically sound reason to do so.

Given this, we believe the government's primary role is to be supportive, nurturing, and coordinating rather than directive and regulatory. The government should continue strong support of research both at universities and, when addressing special mission needs, at inhouse laboratories. Support of centers of excellence, where researchers can conduct state-of-the-art research and simultaneously pass knowledge and know-how to students, is particularly encouraged for this area. Moreover, the government can assist the robotics industry, while simultaneously letting the free market system function, by investing in applications of industrial robots where there is an opportunity to achieve a benefit to the government from productivity improvements and/or cost reductions.

Universities should emphasize longer term research efforts that will provide the technology base that can establish the U.S. as a world leader in robotics and robotics technology. Industry on the other hand, should concentrate on the implementation issues that make this technology impact our economy and national security. By establishing an interface between industry and universities through joint programs, we believe the transition from research, through development, and into implementation will be effectively achieved.

As an alternative to a national plan, the government could encourage voluntary information sharing, perhaps along the lines of DoD's information and analysis centers (IAC's). Such a center could serve as a focal point for collection, review, analysis, appraisal, abstracting, indexing, and storage of information. It could then maintain liaison with interested government agencies and with the private sector. The center could run government/university/industry workshops in areas such as software needs, automated manfacturing systems, and quality assurance, that could establish prioritized needs for research, development, and implementation. Their data bank of evaluated and demonstrated information would assist in technology transfer and perhaps, through the publication of popular expository papers, it could contribute to increased technical literacy of the general population. It could also maintain in its bank, data on scientific manpower in robotics technology to track needs in this area.

From a DoD standpoint, robotics technology provides important manufacturing, maintenance, and military operational opportunities. We believe each agency should determine the size of its program, based on its perceived needs and opportunities, and on availability of qualified technical manpower. We cannot at this time provide precise estimates of FY84 DoD funding for this area. However, in FY83 we will spend $44 million and anticipate growth in funding for this area in FY84.

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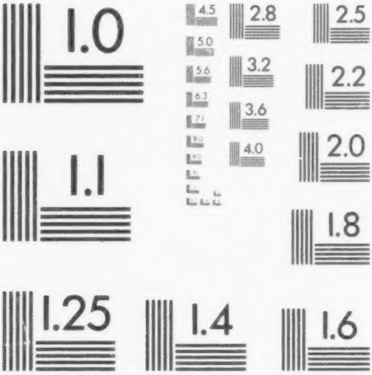
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